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Seaslug test missile

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COVER PICTURE

Seaslug test missile being fired from H.M.S. "Girdle Ness", the guided weapons trials ship, during recent sea trials.

SIR LESLIE GAMAGE, M.C., Chairman and Managing Director of The General Electric Company Limited, who received a Knighthood in the June, 1959, Birthday Honours List.

Nuclear Power Station for Japan

THE G.E.C. is to build Japan's first nuclear power station. In February, 1959, the Japan Atomic Power Company announced that they had opened exclusive negotiations with G.E.C. for the supply of a 150 MW nuclear station to be built at Tokai-Mura, approximately seventy miles north-east of Tokyo. These negotiations have now been concluded and it is expected that the final details of the contract, the value of which will be approaching £20 million, will be settled later in the year. The station will take approximately four years to build and is expected to be in full operation in 1963.

The design submitted in collaboration with Simon-Carves Limited is for a single-reactor power station, and the measures taken to ensure the safety of the installation under earthquake conditions are of particular interest.

In its basic elements, the reactor is similar to those already being built for the British nuclear power programme. The natural uranium fuel elements are mounted in vertical channels through the reactor core which is built up from interlocking graphite units weighing a total of almost 1,500 tons. There are approximately 2,000 fuel channels, each containing eight fuel elements. The core is completely enclosed in a spherical pressure vessel having an internal diameter of 62 ft., and this, in turn, is surrounded by a concrete biological shield approximately 10 ft. thick.

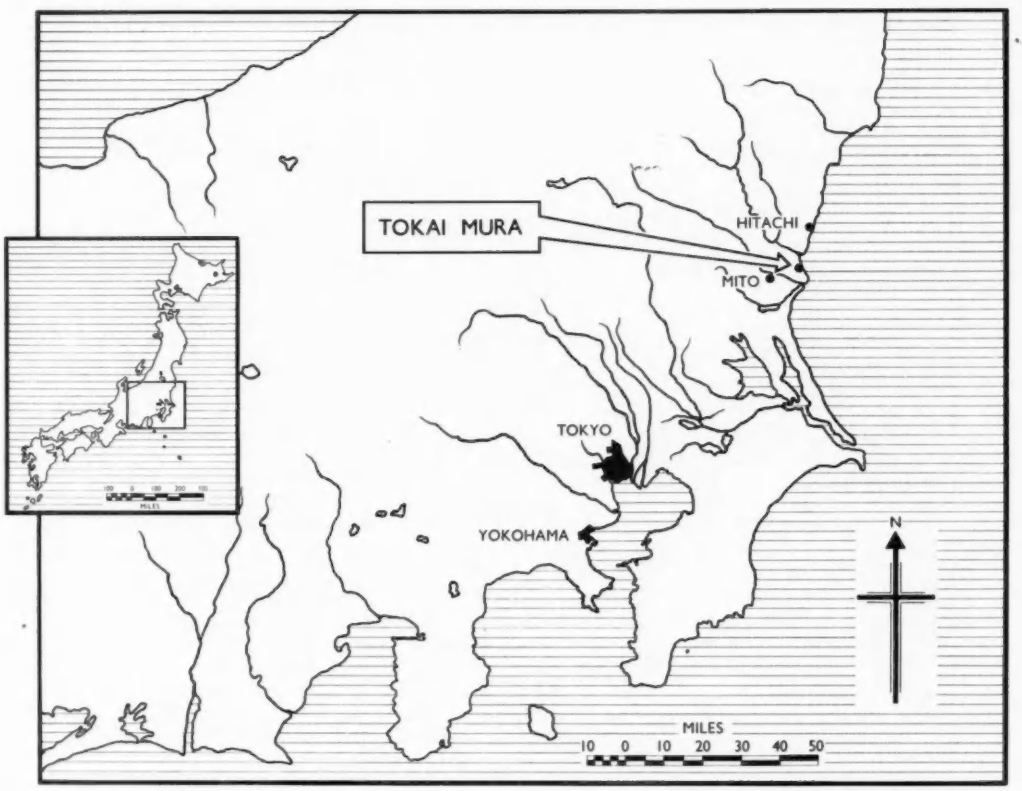


Fig. 1.—Map showing the location of Tokai-Mura.

The heat generated inside the reactor is extracted by circulating carbon dioxide gas through the core. This gas is heated in its passage over the fuel elements and is then led away through 6 ft. diameter ducts connecting the pressure vessel to four steam-raising units, two on each side of the reactor building. In these units the heat from the gas converts water into steam which is then piped to the turbine hall where it is used to drive two 85 MW turbo-generators.

Charging and discharging of fuel elements can be carried out while the reactor is on full load by means of a single machine operating above the reactor. The reactor is provided with the usual type of control system employing neutron-absorbing control rods which can be raised and lowered in vertical channels interposed between the fuel channels through the core. In addition, however, an independent alternative shut-down device, which can be tripped manually and which operates automatically under severe earthquake conditions, has been incorporated in the design. This device is effective even in the event of movement of the core relative to the pressure vessel. Overall control of the operation of the complete power station is effected from a central control room in the reactor building.

SPECIAL DESIGN FEATURES.

In the design of this power station, full advantage has been taken of the valuable experience gained in producing designs for installations in Britain and Europe and in building the Hunterston station. As a result of extensive research and development work, it has been possible to introduce a number of important technical improvements to increase the efficiency of the station. It has been necessary to adopt a modified approach to certain fundamental aspects in view of the potential earthquake hazard in Japan, and the resulting design is fully capable of meeting the stringent requirements laid down by the purchaser to ensure the safety of the installation under the most severe conditions which could arise from this source.

Structural Design and Plant Layout.

One essential requirement in the structural design was to ensure the integrity of the reactor building and its associated steam-raising plant as a complete unit so that no breach could occur in the gas circuits. The concrete substructures supporting the steam-raising units are therefore carried on the main reactor foundation raft to ensure uniformity of movement during earthquakes. In addition, the support system for the gas ducts connecting the reactor pressure vessel to the steam-raising units has been designed so that the stresses in the ducts and in their junctions with the pressure vessel are maintained at safe levels under all circumstances.

As a further measure to ensure the safety of the reactor, the reactor building itself houses all the plant necessary to guarantee the removal of all heat generated within the core, even if severe earthquake shocks should cause the fracture of all pipe connections between the reactor building and the turbine hall.

Reactor Core.

The core of the reactor, including the graphite reflector which surrounds the core proper, is supported inside the pressure vessel on a steel grid of "egg-box" construction and the graphite blocks are held in place by a system of restraints in the form of a framework which encircles the whole core. This framework has been specially designed to hold the core accurately in position even during severe earthquake conditions.

Reactor Pressure Vessel.

The 62 ft. diameter spherical pressure vessel which encloses the reactor core is fabricated from steel plates $3\frac{1}{4}$ in. thick. The steel used for this purpose has been specially selected to withstand the effects of prolonged irradiation.

The sphere is supported on a cylindrical steel skirt, and a further skirt is welded to the vessel near the top. This upper skirt is anchored to the biological shield as a precaution against disturbance during earthquakes.

Vertical standpipes connected to the top of the sphere pass upwards through the top shield, providing a means of access to the reactor core for control devices and charge/discharge equipment. Further standpipes house mechanisms capable of detecting any displacement of the core, pressure vessel or support grid due to earthquakes and of shutting down the reactor before the safety of the installation is jeopardised.

Fuel Elements.

The fuel elements are fabricated from natural uranium metal encased in specially finned cans of magnesium alloy. Each element is individually supported inside its own graphite sleeve. The weight of the stack of elements in a channel is thus transmitted through the sleeves so that stresses on the fuel rods themselves are kept to a minimum. By making the sleeves from a specially treated graphite which has a very low permeability to the coolant gas, it has proved possible to maintain the main moderator graphite at a temperature such that no significant storage of Wigner energy occurs during the life of the reactor.

Since the fuel in this reactor is charged and discharged from above, each element is provided with a grappling device which can be gripped by the charge machine grab. This device is made of a zirconium alloy and is designed so that the cartridge itself cannot be damaged during refuelling operations.

Charge/Discharge Equipment.

In this reactor, the charging and discharging of fuel elements are carried out from above the reactor. It will be recalled that G.E.C. pioneered the development of bottom charge/discharge equipment which offers considerable practical advantages, but this is one of the cases in which it was desirable to modify the design to meet the special local circumstances. By adopting top charging arrangements, the centre of gravity of the reactor building is lowered, thus improving its stability under earthquake conditions.

All normal refuelling operations are carried out, while the reactor is on full load and under pressure, by a single machine travelling on a gantry above the top concrete shield. The same machine is also used for reactor servicing functions including the planned maintenance of control mechanisms. A duplicate machine is installed to provide extra facilities during start-up and to permit the withdrawal of the first machine for maintenance.

employed. Each rod is suspended from a stainless-steel wire rope wound on an electrically driven drum mounted in an extension to the associated top stand-pipe. The driving system provides accurate control of the rod's position in the core, and of its rate of movement at all times.

In addition to the normal control-rod system, there is an alternative shut-down device which would be used only in emergencies.

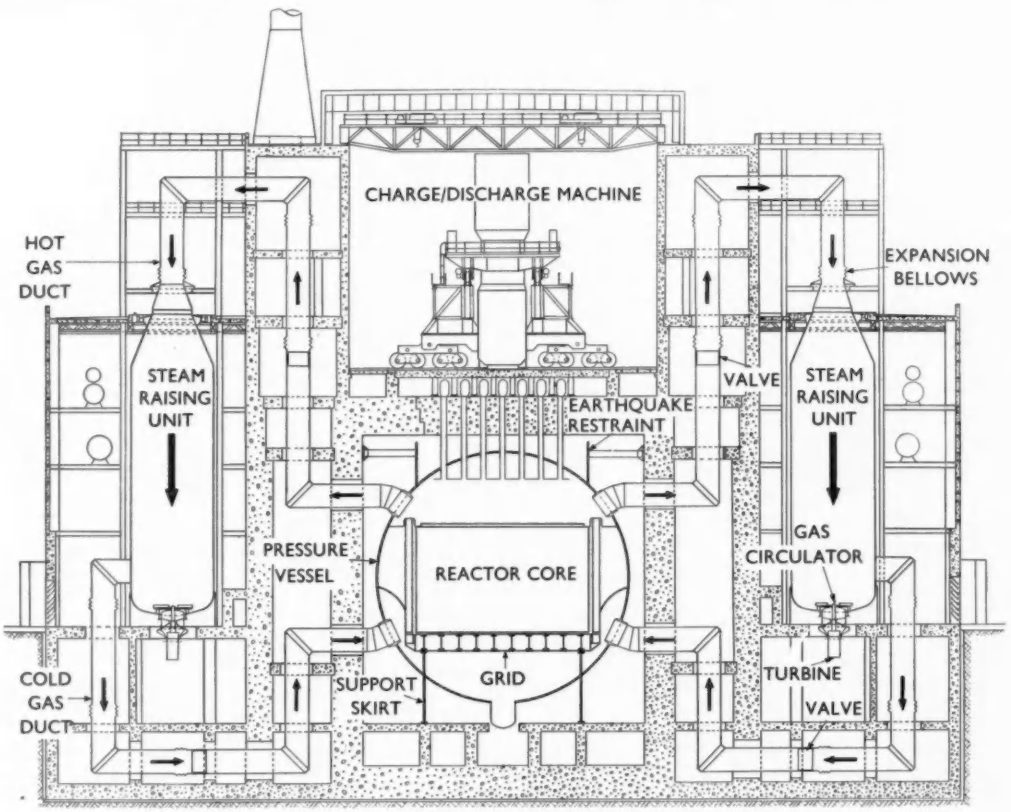


Fig. 2.—Simplified sectional drawing of the reactor.

Each charge machine is remotely controlled by a single operator from a desk housed in a control room at the edge of the pile cap. In order to ensure the correct performance of the machine's functions, highly developed sequence-control equipment is provided, the possibility of error being further reduced by the employment of a punched-card system for setting the requisite interlocks for any given operation. The operator can follow the working of the machine by means of mimic diagrams and closed-circuit television.

REACTOR CONTROL EQUIPMENT.

For all normal reactor-control functions, including emergency trips, the usual system of control rods is

This device comprises a large number of boron-steel balls which can be released into special channels through the core. These balls can enter the core in sufficient quantity to shut down the reactor even in the event of a severe earthquake which might seriously disrupt the graphite structure, and will be effective even if the core is tilted at an appreciable angle from the vertical. The diameter of these balls will be of the order of one inch.

The trips to release the balls can be operated either manually, or by seismic pick-ups outside the station, or by devices sensitive to displacement of the pressure vessel, of the core within the vessel, of the core-support grid, or of various other critical parts of the installation.

One advantage of this type of shut-down device over possible alternatives is that, provided the reactor has not been too seriously damaged, the balls can be removed after the emergency, and the reactor repaired and restarted.

STEAM-RAISING UNITS.

Each of the four steam-raising units incorporates H.P. and L.P. evaporators with economiser and superheater sections. The banks of specially designed finned tubes which make up these various sections are mounted in a cylindrical pressure shell, 84 ft. high and with an internal diameter of 21 ft. 6 in. The tube supports and also the skirt on which the complete unit is carried are designed to withstand earthquake shocks.

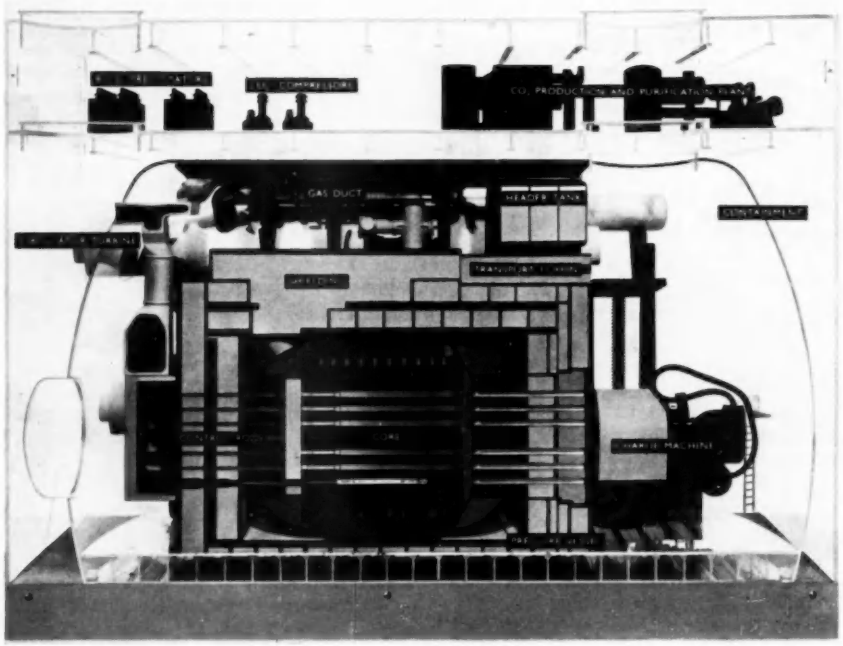
GAS CIRCULATORS.

The carbon dioxide coolant is circulated through the reactor system by single-stage centrifugal blowers. One blower is mounted in the base of the pressure shell of each of the four steam-raising units, thus avoiding the need for large separate pressure casings. Each blower is driven by a steam turbine.

GENERATING PLANT.

Housed in the turbine hall are two 85 MW turbo-generators each comprising a dual-pressure steam turbine driving a hydrogen-cooled alternator incorporating a highly developed system of direct cooling for the rotor. Apart from the normal steam condensers, dump condensing plant is provided for duty during start-up and shut-down.

NEW DESIGN OF NUCLEAR REACTOR



The gas-cooled graphite-moderated nuclear reactor has been further developed by the G.E.C./Simon-Carves Atomic Energy Group to give a compact design suitable for small nuclear power stations or for ship propulsion. Hitherto the size and weight of the British type of reactor has precluded its use in ships, but the new advances have made possible a unit producing 50,000 s.h.p., yet weighing only 2,400 tons. The photograph shows a sectioned model of such an installation.

A Voltage Regulator for Large Power Systems

By V. EASTON, B.Sc.(Eng.), A.M.I.E.E., and K. C. PARTON, B.Sc.(Eng.), A.M.I.E.E.,
Engineering Group, Witton.

THE construction and commissioning of the 275 kV Supergrid, and the continued increase in the size of individual generating units which will be directly connected to it, has focused attention on the problems which may arise in day-to-day running, one of these being the stability of operation on leading power-factor loads. Up to a few years ago this condition would have required the alternators to be designed with a relatively higher short-circuit ratio and, therefore, with an inherently greater capacity to supply leading reactive MVA with a reasonable margin above the steady-state stability limit corresponding to a rotor load angle of 90°. The development of the quick response regulator with no dead band has provided another possible solution to the problem since it permits satisfactory operation at rotor load angles over 90°, i.e. in the dynamic stability region. It is then possible to reduce the short-circuit ratio and to use the margin in rotor excitation so obtained to increase the capacity to supply additional lagging reactive current, i.e. to reduce the rated power-factor to a value more suited to the system conditions.

In the latest development just described it is essential that the performance and reliability of the whole of the regulating equipment is of the highest order and that maintenance is reduced to a minimum. The G.E.C. has many years experience of the application of large magnetic amplifiers in the automatic control of industrial equipment such as colliery winders and rolling mills and also in the design of high-sensitivity, quick-response voltage regulators for special alternators. A major recent development is a magnetic-amplifier voltage regulator of the continuously acting type capable of controlling the largest alternator, and requiring little or no maintenance since the regulating equipment is static.

A most important feature of the regulator is the inclusion of an automatic overriding control, responsive directly to the rotor load angle, which under any loading condition will prevent the excitation being adjusted to such a value that the preset maximum rotor angle can be exceeded. This feature represents a major technical advance in alternator control practice.

Fig. 1.—Type CVR7 voltage regulator.

The new voltage regulator, known as type CVR7, is a continuously acting automatic device with no inherent dead band. As the output voltage of the

alternator tends to alter, the regulator changes the excitation continuously to provide a steady terminal voltage and stable operation over a wide range, including operation in the dynamic stability region, i.e. at load angles above 90°. The action of the regulator under the latter conditions can be briefly explained with reference to fig. 2, which shows the power/angle curve given by $P = \frac{V_1 \cdot V_2}{X} \sin\theta$

where X=alternator synchronous reactance plus system reactance.

V_1=alternator e.m.f. behind synchronous reactance.

V_2=equivalent system voltage.

θ =overall transmission angle.

θ_1=initial steady state transmission angle.

Should the machine angle increase by an amount $\Delta\theta$, there is basically an incremental power difference ΔP tending to *accelerate* the rotor, i.e. to increase θ and cause the machine to run out of step. However, $\Delta\theta$ also causes an incremental drop in the terminal voltage so that the excitation is very rapidly boosted by the automatic voltage regulator (a.v.r.) to form a new effective power/angle curve (shown dotted). There is now a resultant incremental power $\Delta P'$ to retard the rotor and restore the steady state condition.

Because the slope of the power/angle curve becomes steeper as the machine angle increases beyond 90° the power change for a given change of rotor angle will increase. Therefore, for any given regulator there will be a limiting rotor angle above which the rate of increase of incremental torque ΔP will be too rapid to be compensated by the a.v.r. This sets the absolute limit to the range of stable operation ; in practice some margin must be allowed. For every system there is, therefore, an inherent transmission angle, which must not be exceeded if stability is to be maintained. The type CVR7 regulator gives full control up to this limit, after which the type K.A.L. rotor angle limiter automatically ensures that this angle is not exceeded.

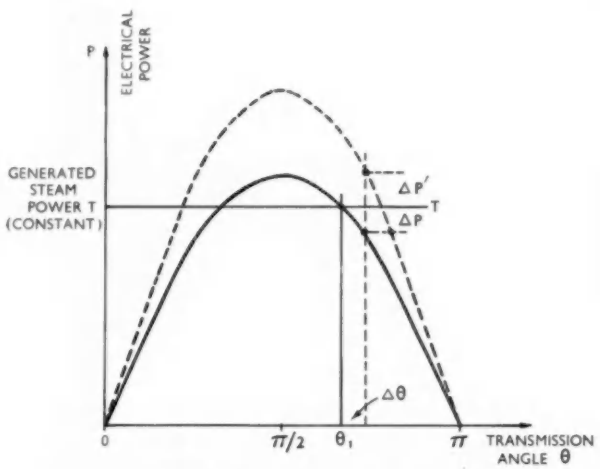


Fig. 2.—Transient power/angle diagram.

OPERATION OF VOLTAGE REGULATOR.

The voltage of the alternator is measured and compared with a fixed reference voltage, and any divergence is amplified by magnetic amplifiers and fed directly to the field of the main exciter. In this way the excitation is controlled to maintain the terminal voltage within ±0·5 per cent of the set value.

A continuously acting regulator of completely static design is thus provided, giving the advantages of great robustness and reduced maintenance requirements. The relays employed in the ancillary control and protective gear have been kept to a minimum. Compounding can be included in the alternator voltage signal to give parallel-running compensation and transformer or line drop compensation as required.

Smooth and stepless manual adjustment of excitation is obtained by controlling the main magnetic amplifier by an induction regulator. This equipment is permanently energised and is not subjected to any switching operations. It is thus always in circuit, and, on automatic control, the a.v.r. circuit only provides transient additional high-speed excitation. This ensures the utmost reliability of the hand-control circuit and simplicity of changeover between automatic and hand control, and is in no way detrimental to the a.v.r. performance.

The auxiliary machines required are the main exciter and a 400 c/s self-excited pilot alternator for energising the a.v.r. equipment. Since both the field and output windings of the pilot alternator are wound on its stator, the number of brush contacts on the whole excitation system is reduced to a minimum, namely those required for the main exciter commutator and the main alternator sliprings. The high frequency output of the pilot alternator allows the magnetic amplifiers to give a very rapid response to system fluctuations, and enables the size of all iron-cored components to be reduced. The basic circuit diagram of the regulator is shown in fig. 3.

Automatic Control.

The alternator terminal voltage is fed to the a.v.r. via the compounding resistor R_2. This voltage is converted from single-phase to three-phase, is rectified, smoothed, and then compared with a fixed reference voltage, derived from a circuit embodying a special heavy-duty type of gas-filled reference tube. For simplicity and reliability, and for the highest accuracy and speed of response, the specially selected industrial gas-filled tube is preferable to any of the more elaborate types of voltage sensitive circuits.

Any difference arising between the reference and terminal voltages is amplified by the magnetic amplifiers MA_3 and MA_2, so that a correcting signal is applied to the coil on the main output magnetic amplifier MA_1

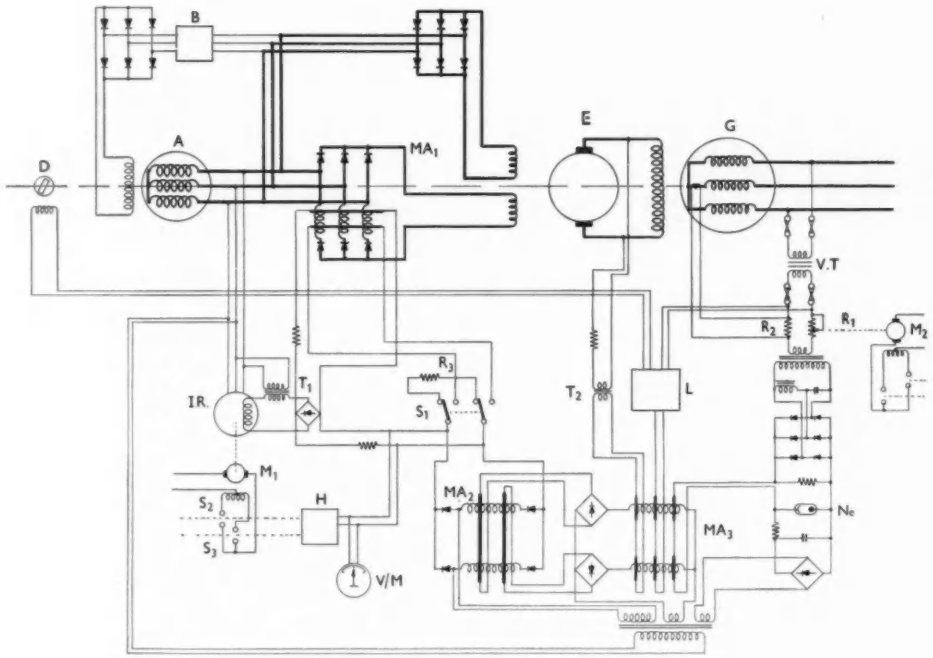


Fig. 3.—Basic diagram of voltage regulator.

KEY

A	*Pilot alternator.*	MA_1	*Main magnetic amplifier.*	R_2	*Current compounding resistor.*
B	*Self-excitation circuit for pilot alternator.*	MA_2	*2nd stage magnetic amplifier.*	R_3	*A.V.R. dummy-load resistor.*
D	*Rotor angle transmitter.*	MA_3	*1st stage A.V.R. magnetic amplifier.*	S_1	*Hand/auto changeover relay.*
E	*Main exciter.*	M_1	*Hand-control induction regulator motor.*	S_2	*Hand control " raise " relay.*
G	*Main alternator.*	M_2	*A.V.R. setting-resistor motor.*	S_3	*Hand control " lower " relay.*
H	*Hand follow-up circuit.*	Ne	*Gas-filled reference tube.*	T_1	*Reference transformer for I.R.*
I.R.	*Induction regulator.*	V.T.	*Voltage transformer.*	T_2	*Stabilising transformer.*
L	*Rotor angle limiter.*	R_1	*A.V.R. setting resistor.*	V/M	*Null balance voltmeter.*

either to increase or decrease the excitation as required. The maximum output voltage obtainable from MA_1 is several times greater than that required for maximum steady-state field conditions, so that heavy positive forcing can be obtained. This feature, together with the inherently high speed of response of MA_1 enables rapid control of the exciter field to be achieved. A negative biasing field is also provided on the main exciter in order to obtain rapid negative forcing.

Once the regulator has changed the excitation, the hand follow-up device will operate to energise the relays of the hand control circuit so that the hand control coil excitation is either decreased or increased to take over the excitation of the a.v.r. coil. Thus, when a steady state is again reached, the current in the a.v.r. control coil of MA_1 is reduced to a very small value and the required steady-state excitation is supplied almost completely by the hand control equipment.

Hand Control.

The output of the pilot alternator is controlled and rectified by the auto-excited magnetic amplifier combination MA_1 and fed to the main exciter field. The control signal for the main control winding of MA_1 is obtained from an induction regulator *I.R.* This arrangement produces stepless excitation control over the full operating range. The induction regulator is motor-driven, the direction of rotation being controlled by the hand-control " raise " and " lower " relays, which are themselves energised by hand controllers on the cubicle and in the control room. To provide for emergency operation, the induction regulator may be directly hand-operated from a handwheel on the front of the cubicle. The handwheel is geared directly to the induction regulator, the gearing being engaged only when the handwheel is unlocked and then held in against a disengaging spring. Local and remote lamps, operated by the " raise " and " lower " relays, indicate that the excitation is being raised or lowered, and they remain dim when the excitation is stationary.

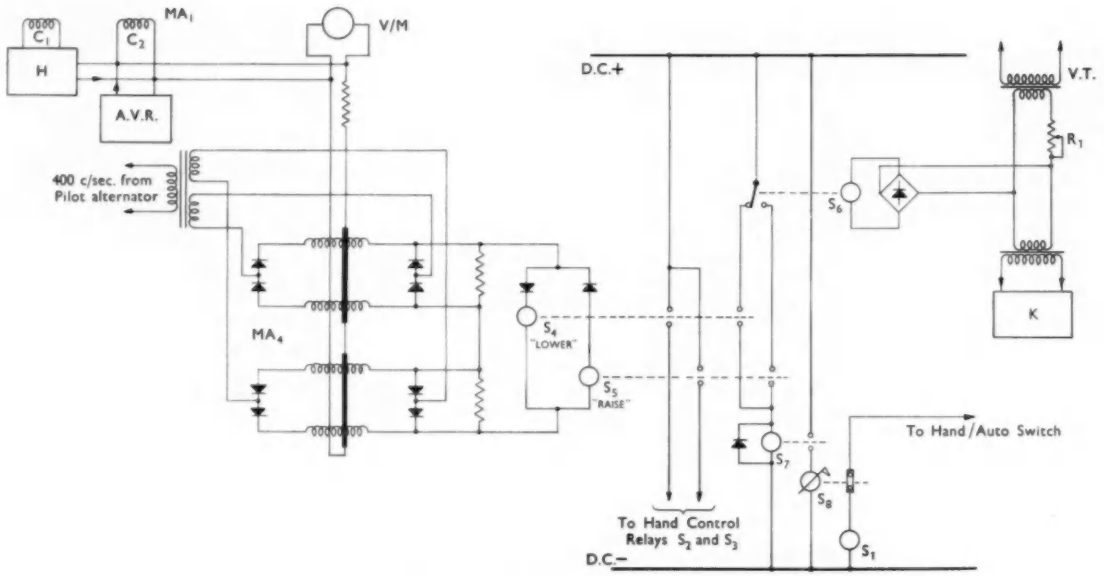


Fig. 4.—Automatic follow-up circuit.

KEY

C_1, C_2	*Hand and automatic control coils of main amplifier* MA_1.
H	*Hand control equipment.*
K	*Reference circuit for A.V.R.*
MA_4	*Hand follow-up magnetic amplifier.*
R_1	*A.V.R. setting resistor.*
S_1	*Hand/auto changeover relay.*
S_4, S_5	*Hand follow-up "raise" and "lower" relays.*
S_6	*Voltage balance relay.*
S_7	*Differential fault relay.*
S_8	*Differential trip relay.*
V/M	*Null balance voltmeter.*

Auto Follow-up Circuit.

On sudden emergency switching from automatic to hand control, it is desirable to have a minimum of system disturbance, and to obtain this an automatic hand control follow-up system is employed to adjust continuously the hand control excitation to approximately the value required by the loading conditions. Because of the system employed on the CVR7 regulator, this means in effect transferring the excitation from the a.v.r. circuit output to the hand control circuit under all steady-state conditions.

The operation of the circuit is shown in fig. 4, where a current proportional to the hand control excitation is subtracted from the a.v.r. output current, and only the difference gives the required component of excitation to the main magnetic amplifier MA_1. This difference output is measured by the null deflection voltmeter and is amplified by the voltage sensitive push-pull magnetic amplifier MA_4, which, depending upon the polarity, causes one of the follow-up relays S_4 or S_5 to close. These relays operate the main hand-control relays to alter the induction regulator setting until the a.v.r./hand difference excitation is reduced approximately to zero. Thus it is only necessary to trip the unexcited a.v.r. control winding C_2 on MA_1 (by opening S_1) to reset to hand control. If necessary, the hand control follow-up can be prevented from running down to a region of low excitation, where a trip to hand control would cause instability.

Protection.

Differential fault protection is afforded by the voltage balance relay S_6 (fig. 4). This relay has a moving contact which, under correct voltage conditions, lies centrally between high and low fixed contacts. Should any fault, such as a component failure, develop in the regulator, it will try to increase the excitation with the voltage already high or reduce excitation when the voltage is low.

In these circumstances, the moving contact will interlock with contacts on one of the hand follow-up relays S_4 or S_5 to trip to hand via the differential fault relay and differential trip relay. On tripping, the "trip to hand" alarm will give audible warning, and the flag on the hand-resetting differential trip relay mounted on the cubicle will indicate the fault. By slugging the differential fault relay a small time delay is provided to prevent inadvertent tripping during transients. The regulator also includes conventional undervoltage protection.

OPERATION OF ROTOR ANGLE LIMITER.

The factors which cause instability in a synchronous machine are largely external to the machine itself. The changes of frequency of large power networks and the action of turbine governors are not fast enough in operation to cause large and rapid fluctuations of the mechanical power transmitted through the driving shaft of the machine. However, the electrical output may be subject to large and sometimes rapid changes due to load variations and to switching. These changes of electrical output are limited only by the characteristics of the power network to which the machine is connected, but they are always associated with a movement of the terminal voltage vector relative to the vector representing the quadrature axis of the machine rotor. This is a common criterion irrespective of load, voltage or system reactance.

The machine angle is the fundamental measure of stability for turbo-type synchronous machines operating in parallel, the theoretical maximum angle depending on the local machine and system conditions. The K.A.L. equipment provides visual measurement of the load angle so that any danger of falling out of step can readily be appreciated. At the same time it is possible to initiate automatic corrective action whenever a preselected load angle is reached.

In these circumstances the stability of the machine could be improved either by reducing the load or by increasing the excitation. The first method would be slow in operation and effect, and would under certain circumstances lead to another form of instability, namely that of loss of frequency control. Increasing the excitation of the machine gives a much faster response and incurs only the disadvantage of a slight rise in the system voltage during the time that the machine is operating near the region of instability. This is achieved with the type K.A.L. equipment by suitable immediate alteration of the calibration of the automatic voltage regulator only at the time when corrective action is needed, so that the regulator

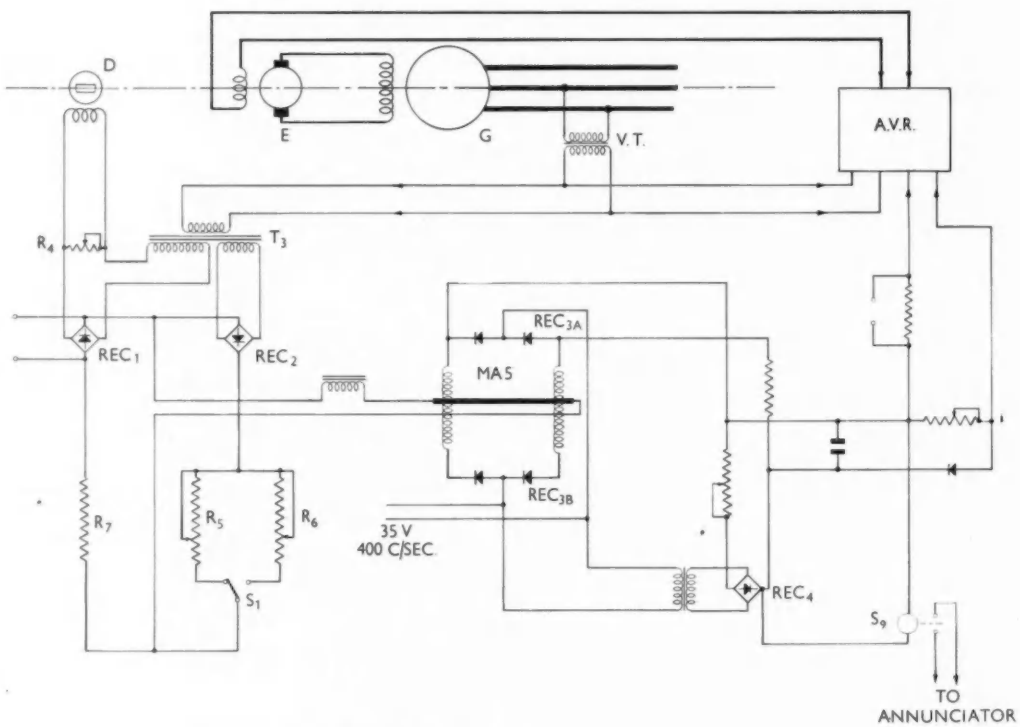


Fig. 5.—Basic diagram of rotor angle limiter.

KEY

D	*Rotor angle transmitter.*	R_4	*Voltage adjustment.*
E	*Exciter.*	R_5	*" Hand " limit setting.*
G	*Generator.*	R_6	*" Auto " limit setting.*
MA_5	*Magnetic amplifier for rotor angle limiter.*	S_1	*Hand/auto changeover relay.*
V.T.	*Voltage transformer.*	S_9	*Rotor angle limit alarm relay.*

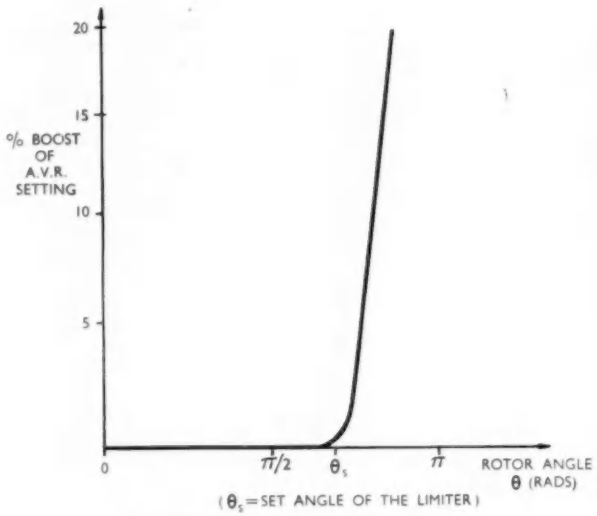


Fig. 6.—Output of rotor angle limiter.

becomes under these conditions a rotor angle regulator, instead of a voltage regulator.

The rotor angle limiter operates in the following manner. A voltage in phase with the rotor quadrature axis is compared with the terminal voltage of the machine, and the circuit is so arranged that when the two are in phase, the resultant output voltage is a maximum, but as the rotor angle increases the resultant voltage decreases. This resultant voltage is rectified, smoothed, and used in conjunction with suitable bias circuits to modify the input to the automatic voltage regulator when the dangerous rotor angle is approached. The net effect is that the excitation of the alternator is instantly boosted to prevent the rotor angle sensibly exceeding the set value. The angle at which this boost occurs may be preset to any desired value. Before this angle is reached, the limiter will be completely inactive. The basic diagram of operation is shown in fig. 5.

The quadrature magnetic axis of the rotor is represented by a voltage generated by a permanent-magnet alternator accommodated in the same frame as the other supervisory generators directly driven from the main alternator shaft. Direct measurement of the rotor angle is essential on this type of regulator, in order to give a correct instantaneous indication of exact rotor angle under both transient and oscillatory conditions.

The phase of the voltage relative to the rotor axis may be adjusted to zero under open-circuit running conditions by rotation of the stator of the permanent-magnet alternator. The magnitude of the output is adjusted to 20 volts by the resistor R_4. The main terminal voltage is obtained from a 110 volt transformer and fed to the transformer T_3, which has two 20 volt secondary windings.

The 20 volt output of one winding is added to the 20 volts obtained from the permanent-magnet alternator, so that under open-circuit alternator conditions (when the rotor angle is zero) the resultant voltage fed to REC_1 is a maximum. When the alternator is loaded, the rotor angle vector will begin to lead the voltage vector by an angle equal to the machine rotor angle. Thus a voltage dependent upon the rotor angle is fed to REC_1, the voltage varying from 40 volts at zero rotor angle to zero volts at 180° rotor angle.

The other secondary winding on transformer T_3 produces a fixed bias current through REC_2, either R_5 or R_6, and R_7. The difference between the bias current and the current through REC_1 will flow through the signal winding of the magnetic amplifier MA_5. As the magnetic amplifier will conduct only when the applied signal is positive, the effect of the bias current, preset by the resistor R_5 or R_6, is to limit the operation of the magnetic amplifier so that only as the dangerous machine angle is approached will the magnetic amplifier become operative.

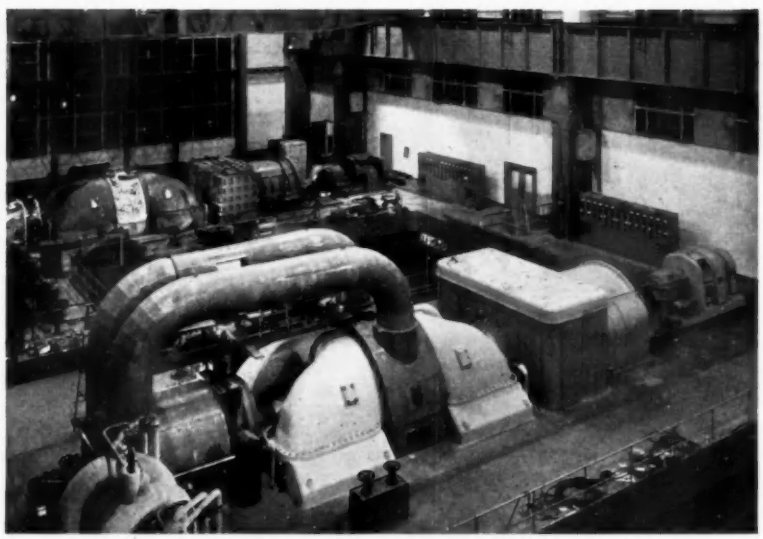


Fig. 7.—60 MW turbo-alternators complete and under construction at Poole Power Station.

The two resistors R_5 and R_6 give a choice of rotor angle limiter setting for hand and a.v.r. control respectively, this arrangement enables a much higher angle limit to be used for automatic control than for hand control. The changeover from one to the other is made automatically by contacts on the "hand/auto" changeover relay.

The output of the magnetic amplifier is rectified by REC_3 and, with suitable bias from REC_4, is used to feed a coil on the main a.v.r. input, the final output being shown in fig. 6. Its function is to boost the excitation rapidly as required, to hold the rotor angle within safe limits. A steady-state condition will then be reached with an input signal to the a.v.r. from MA_5, so that under these conditions the equipment will act virtually as a regulator of rotor angle instead of voltage.

TEST RESULTS.

Some very informative results have been obtained from an extensive series of tests recently carried out on a regulator of this type controlling a turbo-alternator installed by the G.E.C. in the Poole Generating Station of the Southern Division of the C.E.G.B. exciter runs at 1,000 r.p.m. with an overhung 400 c/s homopolar alternator to supply the regulator equipment.

Many synchronous and asynchronous running tests were made to examine the behaviour of the regulator under different conditions and to check its performance under rotor angle control instead of terminal voltage control. The opportunity was also taken to obtain data on machine characteristics not normally available, such as the measurement of the quadrature-axis synchronous reactance, the running as an induction generator with several field circuit connections and the performance of the unit under conditions of coarse synchronising.

TRANSIENT PERFORMANCE.

The response of the excitation system to a sudden change of voltage setting is shown in fig. 8, where the change of signal was such as to alter the generation from 60 MW at unity power factor to 60 MW, 45 MVAr lag. (i.e. 0·8 p.f.). The rapid rise of the main exciter field current indicates clearly the high performance obtained from the 400 c/s magnetic amplifier

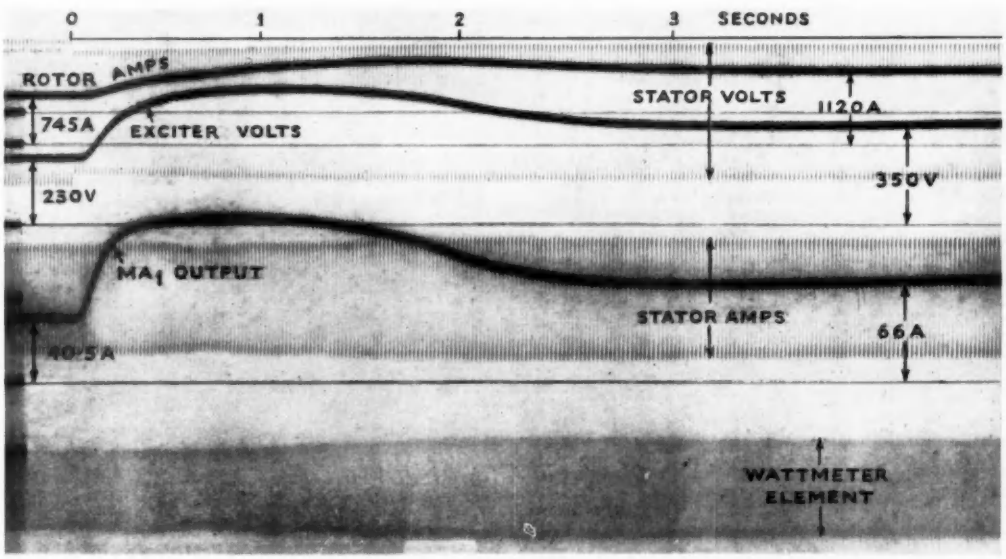


Fig. 8.—Transient step-change of regulator voltage setting.

(fig. 7). The alternator is a 60 MW machine with direct cooling and is the first alternator to be commissioned in this country designed to operate at a hydrogen pressure of 30 lb./sq. in. The physical size of the unit is much smaller than that of a conventionally cooled machine of the same rating. The gear-driven

Test No. 66-A	Date : 24/9/58	Time : 10.31 a.m.
Quantity	Initial Reading	Final Reading
MW	62·24	61·28
MVAr	1·0 lag	43·6 lag
Stator Voltage	11·2 kV	12·3 kV
Stator Current	3,200 A	3,568 A
Load Angle	66°	40°

chain. The terminal voltage can be seen to have attained its final value well within two seconds. The initial dip in the terminal voltage trace is caused by a change of sensitivity applied to this trace as an indication of the instant when the transient kick is applied to the regulator.

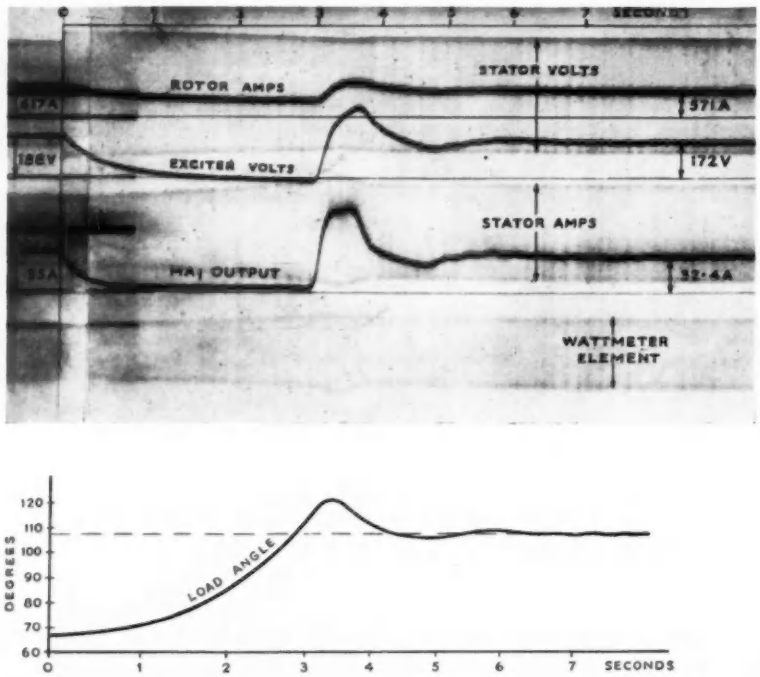


Fig. 9.—Rotor angle limiter preventing instability after a sudden step reduction of the regulator voltage setting.

Test No. 49-B	Date : 23/9/58	Time : 11.12 a.m.
Quantity	Initial Reading	Final Reading
MW	61·2	61·04
MVAr	20·1 lead	56·0 lead
Stator Voltage	13·0 kV	11·93 kV
Stator Current	2,850 A	3,955 A
Load Angle	66°	107·5°

Rotor Angle Limit Control.

The rotor angle limiter is a continuously acting device whose operation may be considered equivalent to that of a stiff spring-loaded buffer, so that if the rotor tends to move beyond the set angle, a signal proportional to the excess angle is applied to boost the excitation to prevent further increase of angle. This was demonstrated, with the unit supplying 60 MW, by adjusting the rotor angle limiter to 70° and then reducing the regulator setting until this value was approached, when the limiter began to have some effect. The first result was the operation of the rotor angle alarm, and subsequent reduction of the a.v.r. setting down to the minimum had negligible effect on the terminal voltage and rotor angle. The alternator excitation was now completely determined by the rotor angle limiter equipment and by altering the adjustment of the limiter, the alternator could be moved round to any load angle within the range of stable operation under normal a.v.r control. This in effect meant that the alternator was on rotor angle control instead of voltage control.

Tests were then conducted to determine the ability of the limiter to prevent a machine falling out of step under adverse transient conditions. In one series of tests the alternator was initially running at a normal load angle at 60 MW and suddenly a drastic reduction of a.v.r. setting was made, giving a resultant zero field voltage on the alternator. Under these conditions the rotor angle limiter invariably provided a "buffer" to the rotor as it attempted to fall out of step, and correctly held the machine on the limiter equipment, fig. 9.

A further example of this is shown in fig. 10, where the rotor angle limiter has prevented loss of synchronism due to the line switching disturbance described below. This is of great interest as it demonstrates that if a set is running at a high angle near the stability limit the rotor angle limiter can ensure that no adverse system switching can cause the machine to fall out of step. It will be noted that the final steady-state load-angle of 107·5° in fig. 9 and 109·5° in fig. 10 are substantially beyond the earlier theoretical limit of 90°, i.e. well inside the dynamic stability region.

Effect of Line Switching Disturbance.

A reactor with a reactance equivalent to approximately fifty miles of 132 kV overhead line was available which could be connected between the generator transformer and the station busbars. Tests were made to study the response of the a.v.r. to the sudden insertion and removal of this reactor. When the alternator was running on a.v.r. control at a high machine angle, it was found that the sudden insertion of the reactor led to a reduced angle of generation and a greater stability margin, and conversely the sudden short-circuiting of the reactor caused an increase in the angle of generation and loss of stability if the initial angle was too high. This is directly contrary to the known effect on normal hand-excitation control. With an initial load of 60 MW at 100° rotor angle and the reactor in circuit, tests were made by shorting out the reactor with and without the rotor angle limiter in service. With no limiter the set immediately fell out of step and resulted in the most severe disturbance to the system experienced during the whole series of

tests. With the limiter in operation stability was easily maintained as mentioned earlier with reference to fig. 10.

Leading MVAr Limit.

Completely stable operation was obtained when generating 60 MW, 66 MVAr lead. at a terminal voltage of 11·25 kV. This gave a transmission angle between the direct axis of the machine and the 132 kV station bars of 120°, and represents a steady-state limit well beyond that likely to be required in practice. The addition of ± 5 per cent current-compounding caused a variation of $\pm 3°$ in the absolute stability limit.

Synchronising on A.V.R. Control.

Tests were made to determine how the machine would pull back into step on a.v.r control once pole-slipping had started. In order to do this the automatic hand-control follow-up equipment was disconnected, and the hand-control induction regulator moved to the zero field position while the set was running on a.v.r. control. To initiate the test, the machine was switched to hand control, resulting in zero alternator field voltage. After several seconds of pole-slipping the set was restored to a.v.r. control, when invariably the machine pulled back into step, even on 60 MW governor setting.

The main reason for this is that during pole-slipping the terminal voltage drops so low that the regulator receives a continuous signal for peak forcing excitation. A powerful resynchronising effect is therefore produced, the result being clearly seen from the oscillogram, fig. 11. The addition of the extra series reactor did not affect the performance.

Opening of the Field Switch on Load.

Further tests were made by running the set on hand control at various power loads at unity power factor, opening the main field switch and reclosing it several seconds later. Results showed that up to 45 MW, resynchronising took place without altering the excitation setting, but above this figure an increase was necessary to pull the machine back into step. This applied generally to tests with and without the field discharge resistor in circuit and also with and without the extra series reactor.

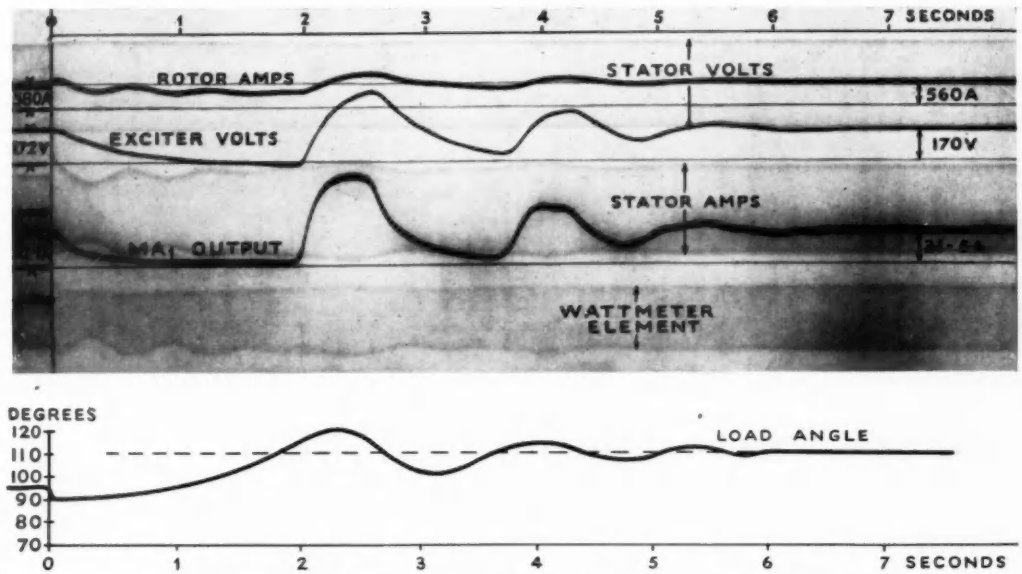


Fig. 10.—Rotor angle limiter preventing instability after line switching disturbance.

Test No. 51-B	Date : 23/9/58	Time : 12.45 p.m.
Quantity	Initial Reading	Final Reading
MW	58·72	58·8
MVAr	31·4 lead	57·6 lead
Stator Voltage	11·45 kV	11·88 kV
Stator Current	3,330 A	3,960 A
Load Angle	95·5°	109·5°

MEASUREMENTS AND RECORDINGS.

Oscillographic records were taken of machine terminal voltage, stator current, MW and MVAr output, rotor current, exciter voltage and field current, rotor angle, speed, governor travel and input steam pressure. The initial and final values of most of these quantities were recorded by substandard instruments specially calibrated and installed for the tests by the Metering Section of the Technical Dept. of the Southern Division of the Central Electricity Generating Board.

plus a transient record. Full evaluation of the records will give valuable new insight into the performance of synchronous machines under many unusual conditions and methods of control.

ACKNOWLEDGMENTS.

In large tests of this nature, where a great number of operating and control engineers are involved, success could not be achieved without the complete co-operation and help of all concerned. In particular thanks are due to Mr. R. H. Coates, Controller of the Southern Division of the Central Electricity Generating Board, for permission to carry out the tests, and to his Technical Engineer and Staff for making all the necessary system preparations and protective gear setting arrangements ; to the Staff at the Bristol Control Centre for their continuous co-operation ; to the Central Electricity Generating Board, Bankside House, and Messrs. Merz & McLellan for active help and encouragement ; to the Superintendent of Poole Power Station and his Staff for their excellent co-operation and the facilities that were made available ; and to the C.E.G.B. London Division for supplying and operating the stroboscopic rotor angle indicating and recording device.

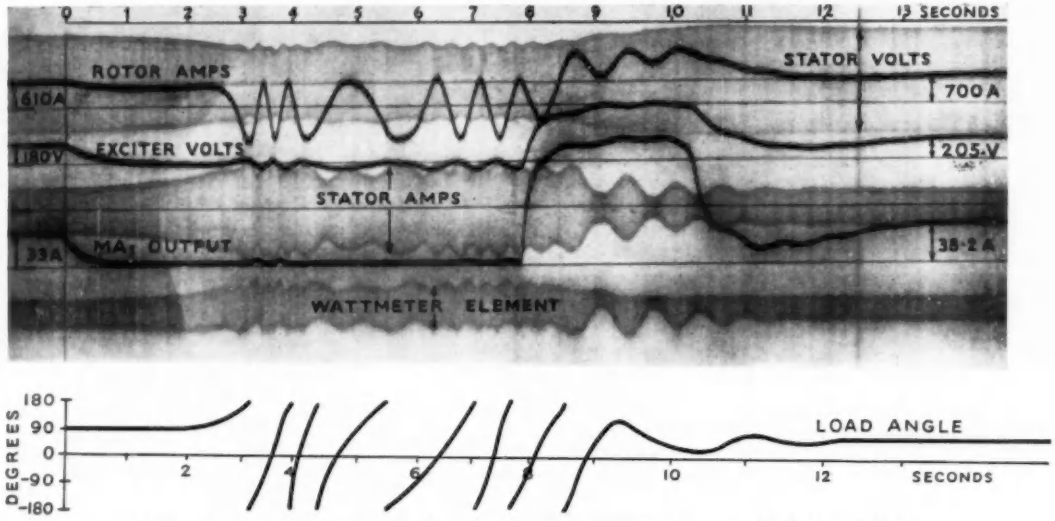


Fig. 11.—Restoration of synchronism by switching to a.v.r. control after removal of field at 60 MW.

Test No. 28-A	Date : 26/9/58	Time : 1.05 p.m.
Quantity	Initial Reading (before removing field)	Final Reading
MW	60·64	58·0
MVAr	33·5 lead	0·7 lead
Stator Voltage	11·05 kV	12·12 kV
Stator Current	3,600 A	2,750 A
Load Angle	94·5°	59°

The rotor angle indicating instrument which forms part of the normal a.v.r. equipment is scaled 0°-160°. This meter, which is installed in the control room, proved of great value during the tests. A second instrument was provided to indicate the overall transmission angle between the rotor and the 132 kV busbars, and both meters agreed in general to within 1° with readings taken by stroboscopic shaft equipment. This equipment, developed and operated by the London Division of the C.E.G.B., provided recordings and a running commentary which considerably facilitated the control of many of the tests.

Altogether over seventy tests were made, of which a great proportion required initial and final readings

Static Sequencing and Positional Control Systems

By S. A. G. EMMS, B.Sc., and G. E. LITTLE,
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INTRODUCTION.

As automation technique progresses there is an increasing requirement in industry for the storage, selection and implementing of operation programmes, which often include one or more positional sequences.

Typical examples are machine punch and press tools, which have to perform a series of punching or bending operations upon each work piece, and reversing rolling mills, which have to effect a number of passes each requiring a re-positioning of rolls and manipulators associated with speed and direction controls of the main and auxiliary drives. Such installations involve heavy duty for the control apparatus, sometimes in difficult conditions of heat and metallic dust. For instance, the manipulator control elements of a hot reversing mill may make 60,000-100,000 movements per week. If such an installation is to work automatically, it is evidently advantageous that the number of moving parts should be as small as possible.

The advent of the cold cathode triode and its associated " gated " circuits has made possible the evolution of control schemes to satisfy these requirements.

THE COLD CATHODE TRIODE.

This device, which is the basis of the selection and sequencing portions of any scheme, is a small discharge tube containing a mixture of neon and argon at low pressure. It has three electrodes : anode, cathode and trigger.

A positive voltage applied between trigger and cathode causes a glow discharge, which, in turn, initiates in the presence of a positive anode-cathode voltage a glow discharge between anode and cathode which continues in the absence of the trigger-cathode glow discharge until the anode voltage is interrupted or considerably reduced.

Since there is no cathode heater, the tube uses no power except when actually conducting, and when used with correctly designed circuits a working life in excess of 10,000 hours is to be expected.

CIRCUITS.

A convenient and reliable method of operating cold-cathode tubes in " logic " circuits is that of voltage transfer, which has previously been described in this Journal* and elsewhere.

In this system, it is arranged that the steady output from a tube is of sufficient magnitude to fire another tube ; the presence or absence of a signal from an intermediate tube may then be used to control the passage of a signal from the first to the third tube.

Thus, in fig. 1, a signal on the trigger of *T*1 will cause this tube to conduct, but the circuit through the rectifier *MR* and *R*2 passes enough current to keep the voltage appearing on the trigger of *T*3 below the firing value. If a signal is now applied to the trigger of *T*2, sufficient to fire the tube, the voltage across *R*2 rises and prevents *MR* from conducting, so that a firing voltage appears on the trigger of *T*3 and an output voltage across *R*3.

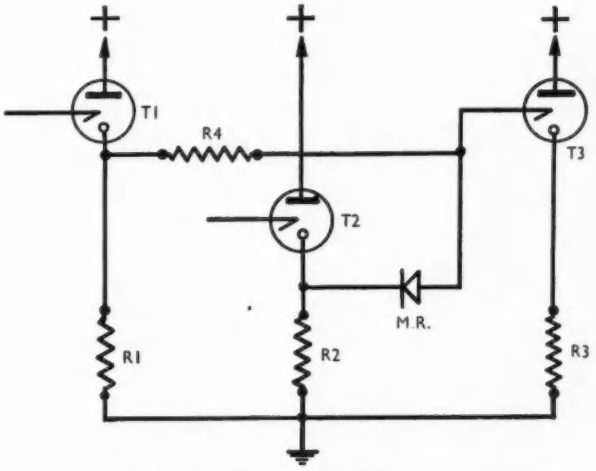


Fig. 1.—Signal transfer control circuit.

A range of " gating " circuits has been developed which may be assembled to perform a wide range of

* *G.E.C. Journal*, Vol. 25, pp. 113-119, April, 1958.

logic functions. One simple arrangement of three such elements is shown in fig. 2.

The arrangement marked " Gate B " in fig. 2 is known as an " AND " gate and it will be understood that a signal from *T*1 will be ineffective, since it will be by-passed to ground by the rectifier *MR*1. If, however, *T*1 and *T*2 are both conducting, the voltage across the resistor *R* blocks rectifier *MR*1 so that the signal is passed on to *MR*2. The small capacitor shown ensures that, when a sharply rising signal reaches the rectifier input to the gate, the resulting spurious output signal arising from rectifier capacitance is diverted to earth.

Gate " C " is known as an " Input OR " gate, and it will be seen that a signal via any one of the rectifiers *MR*2, *MR*3, *MR*4 will cause *T*3 to strike.

Gate " A ", the " Output OR " gate, permits the combination of output signals from a number of tubes in order to control " AND " gates. Minor circuit variations may be made to satisfy special conditions.

Another basic circuit, fig. 3, is employed when tubes are required to be mutually extinguishing. In such cases a common anode resistor is used for the tubes, while a capacitor and series resistor are connected in parallel with the cathode resistor. With *T*1 conducting the capacitor *C*1 will be charged to the cathode-earth voltage. If *T*2 is struck, its cathode voltage will at first rise due to current in *R*5 and will continue to rise slowly as *C*2 charges. The anode voltage will in consequence fall initially and then rise slowly with the cathode voltage of *T*2. As the charge in *C*1 prevents the cathode of *T*1 from following the depression in anode voltage, *T*1 is extinguished and its cathode voltage falls as *C*1 discharges. When tubes are not intended to be mutually extinguishing, their anodes are connected to the H.V. supply and their cathodes to earth via a resistor. In such circuits the anode supply must be interrupted to extinguish the tube.

It is convenient to adopt symbols for the various

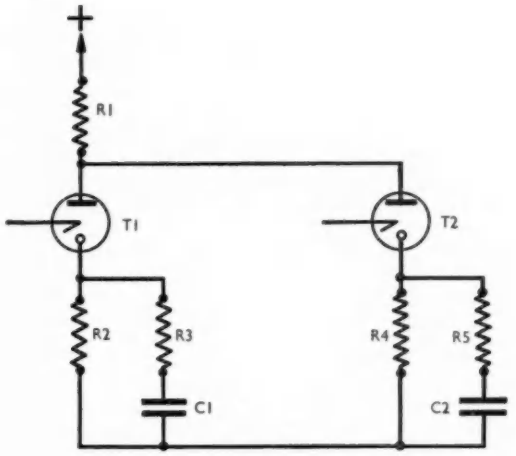


Fig. 3.—Mutually extinguishing tubes.

circuit elements to enable a simplified " logic " scheme to be evolved before the complete schematic diagram is drawn.

Some of these symbols are used to enable a " counting chain " to be illustrated. Such a chain is shown in fig. 4 and is employed as a stepping device for each operation of a series, for example the pass sequence of a rolling mill screwdown. One convention used in this diagram is that groups of mutually extinguishing tubes are shown on a single horizontal or vertical line.

If a start signal is applied to *S*1, a corresponding voltage will appear at the output of " ODD " *E* gate, and if a pulse is then fed into the " Y " lead *L*1 will fire. The following " X " pulse fires *L*2, extinguishing *L*1 and stepping the count from *S*1 to *S*2. Before the arrival of the next " Y " pulse, the output of *S*1 has disappeared and in its place the output from *S*2 is available at the " EVEN " *E* gate. Thus the " Y " pulse fires *L*3 and hence *L*4 fires, stepping the count from *S*2 to *S*3 and so onwards.

It is evident that the firing of each " S " tube can be made to initiate a particular operation, or pass, in a rolling schedule.

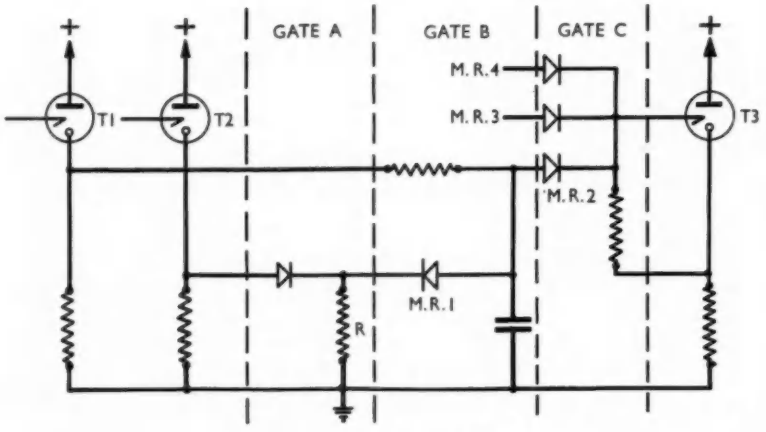


Fig. 2.—Typical gating circuits.

PROGRAMME STORAGE.

Programme storage is effected by using diode " AND " gates to control the passage of signals between any two sets of tubes. A simple circuit is shown in

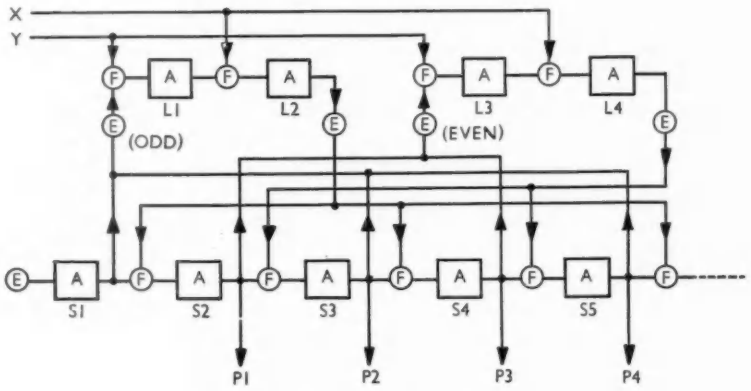


Fig. 4.—Circuit of " counting chain ".

fig. 5. The gate is opened by signals fed in accordance with the operation sequence described above.

Fig. 5 also illustrates an economy which may be effected when several programmes, at certain points, call for similar instructions to a positional servo. One " AND " gate is opened by a combination of all programme signals fed through an " OR " gate. Having thus routed the signals for any particular pass or operation, to its programmed level, the output signal may be used to set up a reference level. For example, each signal may be fed to the appropriate tubes of a three-stage decimal chain via three " OR " gates and will then give a reference level accurate to one part in 1,000.

APPLICATION TO POSITIONAL CONTROL.

The circuit shown in fig. 4 may also be adopted to act as a " count " and " uncount " chain operated by three successive pulses, the direction of the count being determined by the order in which the three pulses arrive at the counting chain. Forward counting is achieved with the circuit as shown in fig. 4, while extra " AND " gates are added for reverse counting, these extra gates being operated by a further four-stage " L " chain.

In this way a digital reset circuit may be constructed which obviates the necessity for " digitisers " having special coding arrangements, since a simple pulse generator can be used in their place. This pulse generator can be mechanically robust and is more suited for direct coupling to the controlled mechanism where the site conditions are arduous.

A digital reference and reset circuit is thus obtained in which the reset is directly coupled to the controlled mechanism. The system is self-monitoring and contains no moving contact surfaces, so that reliability is improved while maintenance is reduced and simplified.

Assuming that a reference level has been established for a further operation, then an error will exist between the position of the equipment and the new reference. This error will exist as the digital difference between the reference and reset decimal counting chains.

A sequential decade sweep circuit can now be used which will step forward at a given rate, providing coincidence signals whenever tubes having the same decade position in the reference and the reset chains are found to be conducting. Stepping signals are thus obtained and the order in which the two signals arrive can be used to determine the sign of the error signal.

For example, the reference level in a decade ring may be considered to have fired on tube 3 while the reset level available may be fired on tube 6. A decade sweep, firing sequentially from 1 to 10, will thus establish coincidence first with the reference tube and later with the reset tube. Two " L " chains similar to that shown in fig. 4 can now be used and the sign of the error will be stored in one or other of them depending on the order of arrival of the coincidence signals. The stored error sign signal may then be transferred at the end of the sweep to tubes used to set an " UP " or " DOWN " error signal into the final control amplifier. As there are three decades in a system, switching to one part in 1,000, the coarse decade error sign signal must be arranged to override the medium error sign signal and, similarly, the medium error sign signal must override the fine error sign signal.

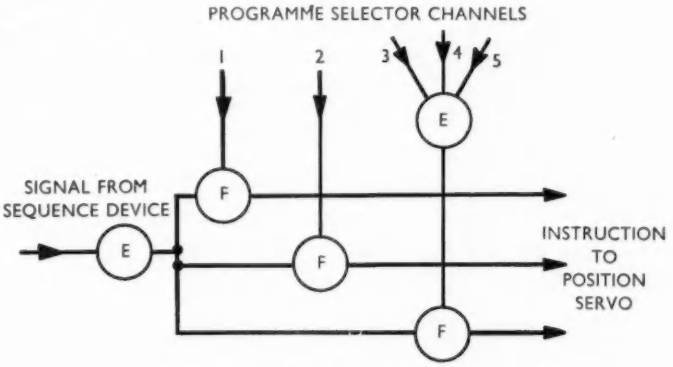


Fig. 5.—Programme storage circuit.

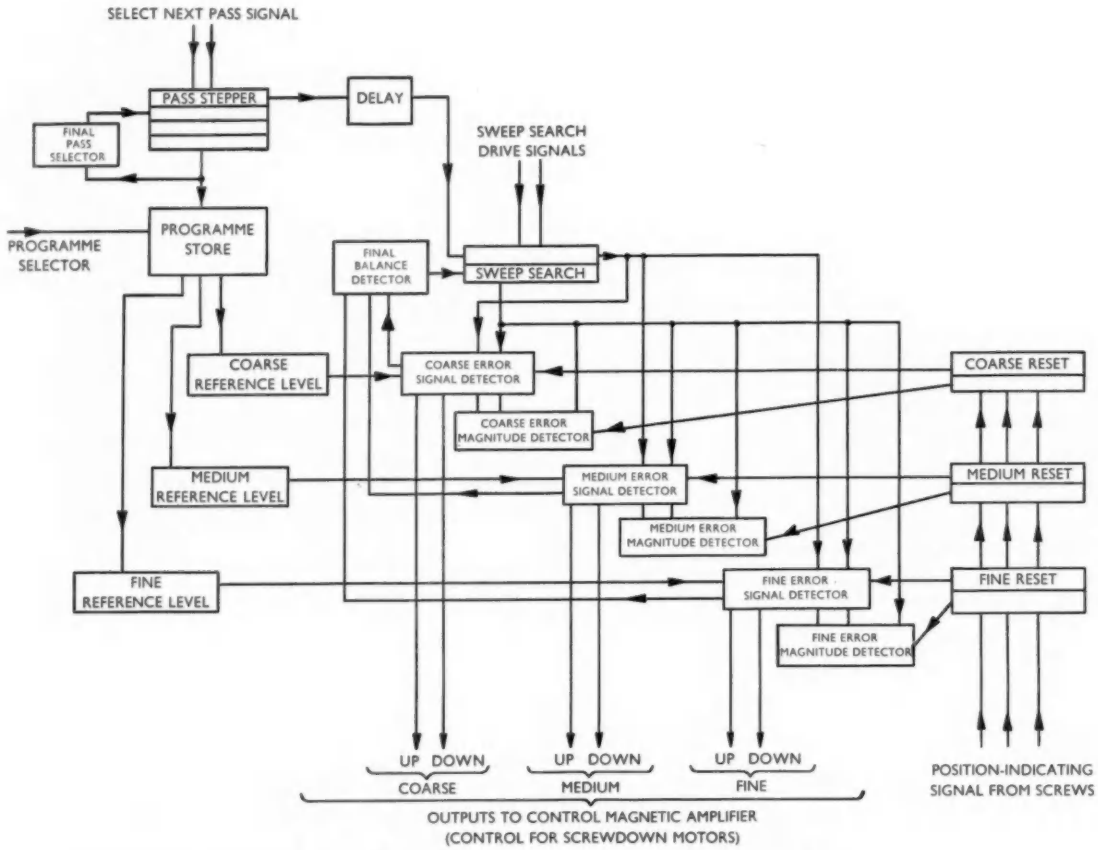


Fig. 6.—Typical diagram of digital decade position control system.

Difficulties can be encountered in a decimal digital counting chain if the position of the remaining reset digits is used as a method of indicating balance. It is therefore convenient to use a secondary reset chain, which measures the magnitude of the digital error during the sweep inspection of the reference and primary reset chains, and which uncounts the established magnitude as the system runs into balance.

The servo control scheme can thus be switched off or on according to a chosen magnitude of error; its direction of motion will be determined by the sign of the error.

The error sign outputs of the three decimal chains can be used to control the output of a push-pull magnetic amplifier into which can also be fed any proportional or derivative stabilising signals that may be required.

SYNCHRONISATION.

Synchronising the reference and reset chains to the controlled mechanism position can be carried out by injecting a false balance signal and a chosen reference and reset signal, and adjusting the position of the controlled device to a pointer or caliper reading which agrees with the chosen reference and reset levels.

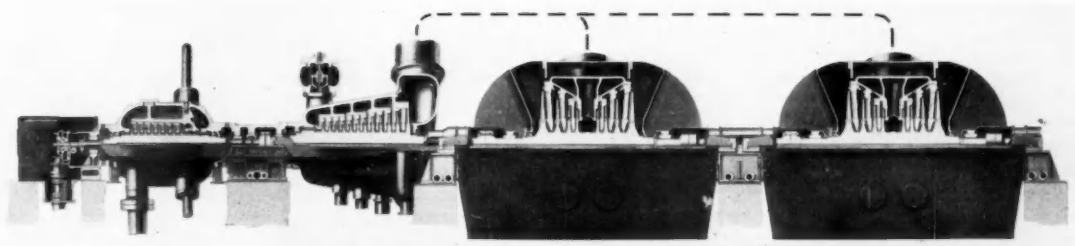
INCREMENTAL CONTROL.

Manual control of the final control amplifier, or a manual offset of the reference level, can be provided to cater for unusual short-term conditions which cannot normally be programmed.

FURTHER DEVELOPMENTS.

The methods described in this article are based on the use of the cold cathode triode; the switching operations involved could be performed equally well by some of the many semiconductor devices now available.

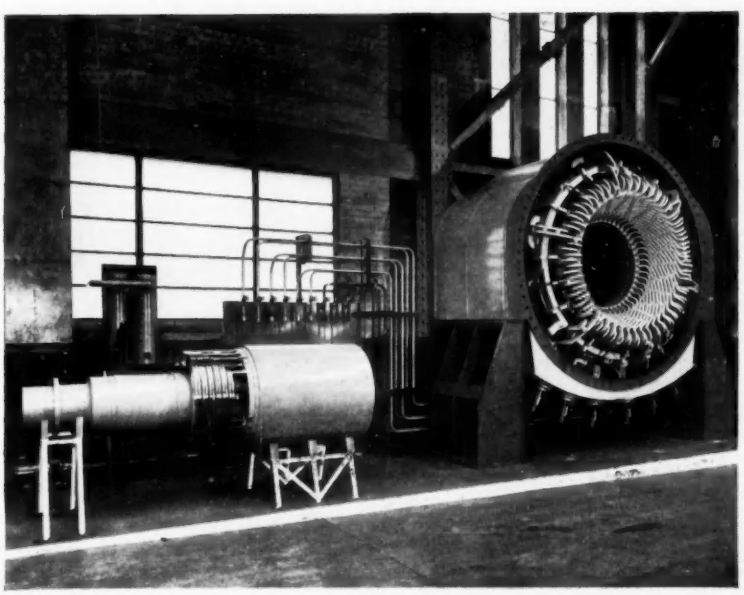
200 MW Turbo-Alternators for Scotland



Section through a G.E.C. 200 MW reheat steam turbine.

The G.E.C. has received an order for two 200 MW turbo-alternators for the Kincardine Generating Station of the South of Scotland Electricity Board. The sets are the largest so far ordered for a Scottish power station, and the order includes the condensing and feed heating plant.

The turbines will be designed for steam conditions of 2,350 lb./sq. in., 1,050 deg. F. with reheat to 1,000 deg. F., and a final feed temperature of 460 deg. F. The alternators will embody hydrogen-cooled rotors and water-cooled stators. The system of water-cooling, which involves only the minimum departure from established winding practice, was described in the July, 1957, issue of the *G.E.C. Journal*.



Model of a water-cooled stator and hydrogen-cooled rotor for a 200 MW alternator.

Developments in Power Rectifiers

3.—MEDIUM VOLTAGE RECTIFIERS

By J. H. HOLLIDAY, D.F.H., A.M.I.E.E.,
Research Laboratories.

IN the introductory article* in this series " medium voltage " for power rectification was defined as between 250 volts and 3,000 volts d.c., the output current being greater than 10 amperes. The types of rectifier that can be used in this voltage range include mercury arc, gas-filled hot cathode, contact, and semiconductor power rectifiers.

The choice of a particular rectifier will depend upon many considerations, such as the output voltage of the complete rectifier equipment, operating efficiency, overload capacity, ambient temperature range, amount of auxiliary equipment, life and maintenance. The type of transformer connection that can be used, and the smoothness of the output current may also be very important.

In the voltage range considered some of the main uses for large d.c. power supplies are electric traction, electrochemical manufacture, and motor drives for such applications as drawbenches, steel mills, printing presses and winders.

MERCURY ARC RECTIFIERS.

During the past twenty-five years these rectifiers have provided the bulk of the rectified power at medium voltage. Manufactured in a wide range of power ratings, they are reliable, efficient, capable of carrying large currents with heavy overloads, and can normally stand high-voltage surges without difficulty. The large current-carrying capacity is a result of two factors. Firstly copious emission of electrons can be obtained from the almost indestructible mercury cathode. Secondly, the action of a positive anode in drawing electrons through mercury vapour produces ions which neutralise the electron space charge effect, and thus allows low forward voltage drops of the order of 12 to 24 volts to be obtained between anode and cathode. The breakdown voltage of mercury vapour in the temperature range used is also very high. This property, coupled with the fact that the anode materials used give very small electron emission under ion bombardment, enables very high peak inverse voltages to be withstood.

The range of temperature normally specified for the ambient air, without derating, is 10 deg. C. to 40 deg. C. Some types of pumpless steel tank rectifiers are capable of operating from temperatures as low as 0 deg. C.

*G.E.C. Journal, Vol. 24, p. 167, October, 1957.

The first mercury arc rectifiers were built at the turn of the century, and subsequently a considerable number of different types were evolved. Some of these will now be briefly described.

MULTI-ANODE RECTIFIERS—GLASS BULB.

These rectifiers are usually made with either three or six anodes fitted into L-shaped anode arms attached to a condensing dome. Air cooling is used with the rectifier suspended in a sheet steel cubicle over a fan.

Because of cooling and de-ionisation problems the effective size of these rectifiers, and also their ratings, corresponds to an output of about 400 amperes d.c., necessitating a multiplicity of bulbs, auxiliaries and circuit complication for large powers.

Some saving in floor space has been made possible by a development in which four unsymmetrical three-arm bulbs are grouped in a cubicle over a common fan. The need for anode fuses, and the influence of high working voltage and heavy duty cycles on the life of glass bulb rectifiers are offset by the ease of replacement, but the majority of applications are for voltages below 1,000 volts d.c.

MULTI-ANODE RECTIFIERS—STEEL TANK.

A variety of designs is found in multi-anode steel tank rectifiers including those with either air or liquid cooling, and either continuously pumped or pumpless.

The general practice in Europe over the past twenty-five years has been to use pumpless, air-cooled rectifiers of the type pioneered by the G.E.C. in 1933. Fig. 1 illustrates a modern version which has a direct-current output of 1,250 amperes, with additional overload capacity, at direct voltages up to 1,500 volts. Experience since 1933 shows that pumpless rectifiers can operate for at least twenty years without replacement or even factory reconditioning. Since 1945 many improvements in the vacuum processing of rectifiers have occurred, such as the use of the helium mass spectrometer for leak detection and of the high temperature vacuum furnace[1] for treatment of components such as anodes and grids. Also, the improvements now being made in welding and brazing techniques should result in a further increase in the life of a modern pumpless rectifier.

The usual practice is to have six anodes fitted either into L-shaped anode arms which themselves are attached to a central condensing chamber, or alterna-

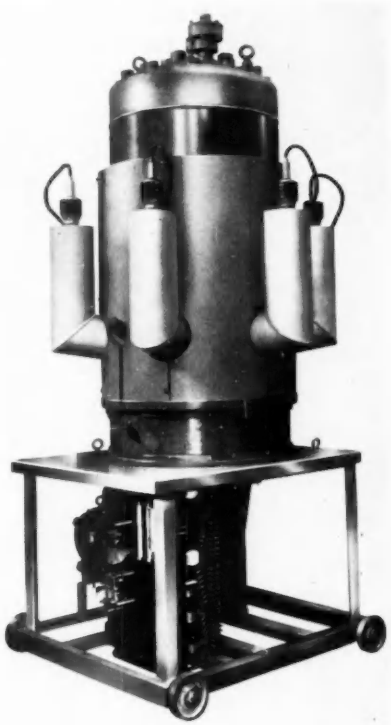


Fig. 1.—G.E.C. multi-anode, air-cooled, steel tank rectifier, with excitation gear and cooling fan. Rating 1,250 amperes and peak inverse voltage up to 3,000 volts.

tively for the anodes to be mounted directly in the main tank. Both types are used extensively and cover a direct-current range of about 300 to 1,500 amperes at output voltages up to 3,000 volts.

Continental practice also includes continuously pumped air-cooled rectifiers for which ingenious designs of vacuum pumps have been developed.[2] These pumped rectifiers are physically very large but ratings as high as 3,000 amperes can be obtained at output voltages up to 3,000 volts.

In America the multi-anode rectifier has been very little used. This is largely the result of the discovery by Slepian and Ludwig in 1933 of the ignitron principle which is used to its greatest advantage in single-anode rectifiers. Consequently, on that continent today, the single-anode type is found in the great majority of rectifier installations.

SINGLE-ANODE RECTIFIERS.

Here again subdivisions can be made which include rectifiers which are either air- or water-cooled, and either continuously pumped or pumpless. Also two distinct methods of igniting the main anode exist, one in which a continuously excited d.c. auxiliary anode is used, and one in which the auxiliary arc is initiated every cycle at the supply frequency. Rectifiers using these two different principles are called excitrons and ignitrons respectively.

The advantages usually claimed for single-anode rectifiers over multi-anode are the greater flexibility in both handling and circuit arrangements, lower arc losses, smaller volume per kilowatt output, ease of replacement and the adoption of mass production methods. On the other hand, because more individual rectifier units are needed for a given power output, the single-anode rectifier normally requires more auxiliary equipment and an increased number of vacuum systems. As the individual single-anode rectifier outputs increase, however, these disadvantages may to a great extent disappear for rectifier equipments of very high loading.

Ignitrons.

In this type of rectifier, the main anode is made to conduct by putting heavy current pulses through a high resistance ignitor rod which dips into the mercury cathode. It is possible, by varying the phase of the pulsed current to the ignitor, to vary the d.c. output voltage in a similar manner to a grid-controlled rectifier. In early designs a very simple internal construction was used and arc drops as low as 12 volts were claimed.

It was subsequently found that an auxiliary anode must be incorporated in order to be certain that the main anode is operative every cycle. This auxiliary anode conducts when the ignitor rod is pulsed, and continues to conduct for the same period as the main anode, thus ensuring that no "misfiring" of the main anode occurs. It has also been found necessary in practice to incorporate de-ionising grids and anti-splash barriers in the arc path in order to prevent arc-back, and these have made the arc drop of the same order as multi-anode rectifiers of similar rating, that is about 18 to 20 volts.

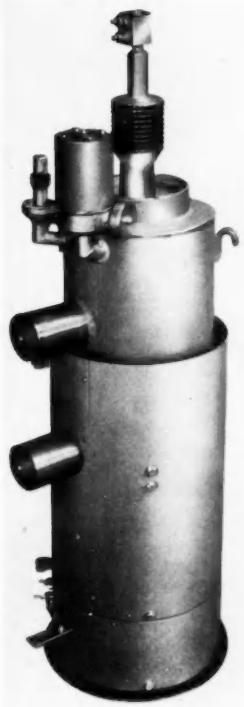


Fig. 2.—G.E.C. single-anode air-cooled excitron. Rating 150 amperes, peak inverse voltage 2,000 volts.

The ignitron rectifier has been developed almost exclusively in America and its manufacture and use have been mainly confined to that country. In its most modern form[3] it is capable of maximum mean currents of 750 amperes at peak inverse voltages of up to 6,000 volts, and can sustain the heavy overloads typical of the mercury arc discharge. The ignitron is of a very robust construction, and does not require cathode insulation. This can be omitted because of the re-ignition of the cathode spot every cycle, which allows the spot insufficient time to leave the mercury surface and wander on to the tank, where it could easily cause arc-back. As a result of intensive development the ignitron is now regarded as a very reliable rectifier and lives of more than five years are confidently expected. To obtain the maximum output power, water cooling is used predominantly and the problems associated with this type of cooling have been solved.

For many years it was thought necessary to evacuate these rectifiers continuously because of their small volume, large current output, and the practice of water cooling. As a result of recent developments both in vacuum technology and in the use of materials, the modern trend is towards pumpless ignitrons.

Excitrons.

The principal difference between the ignitron and the excitron is that in the latter a continuously conducting auxiliary anode is used to ensure that the main anode conducts regularly and that misfiring does not occur. The small pumpless air-cooled excitron which is illustrated in fig. 2 is suitable for mean currents of about 150 amperes at peak inverse voltages of 2,000 volts. These rectifiers are of medium size, easy to handle and their expectation of life is comparable with that of the multi-anode rectifier.

Other very large capacity excitrons are manufactured on the Continent[4] and in America,[5] and these have mean continuous current ratings as high as 750 amperes when liquid cooling is employed. A particular rectifier design may often be used with air cooling instead of liquid cooling but this results in a substantial reduction of rating, possibly by as much as 50 per cent.

One of the most recent developments in the excitron field is the G.E.C. "COM-PAK" mercury arc rectifier. In recent years the need arose for a very small and efficient rectifier, particularly for such applications as underfloor mounting on motor coaches for the new a.c. electrification programme of British Railways. Figs. 3(*a*) and 3(*b*) show the smallest

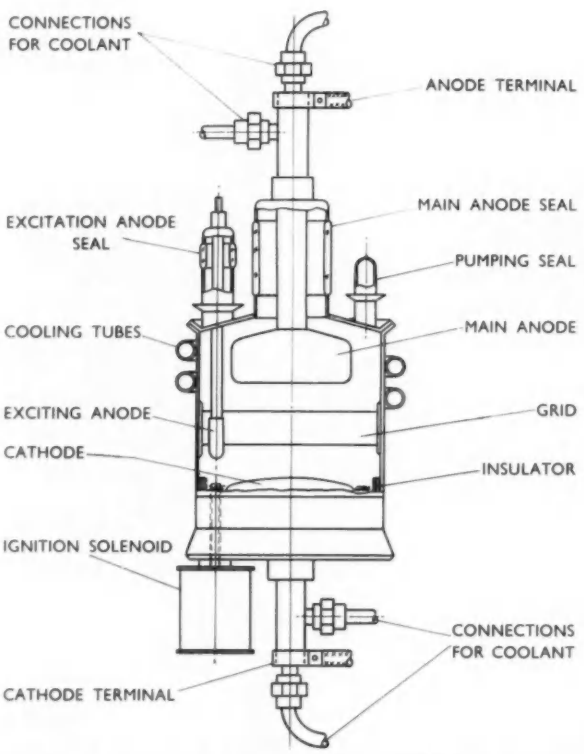


Fig. 3(a).—General arrangement of the "COM-PAK" rectifier.

Fig. 3(b).—G.E.C. single-anode, liquid-cooled, "COM-PAK" excitron (C7-MK1 7 in. diameter). Rating 120 amperes, peak inverse voltage 2,500 volts.

rectifier of this type, which is rated to give a mean continuous current of 120 amperes at a peak inverse voltage of 2,500 volts. A larger capacity rectifier has also been developed and gives a continuous output of 240 amperes at a peak inverse voltage of 3,000 volts. Both these rectifiers have a capacity of 200 per cent of their rated current for 15 seconds, and conform generally with B.S.1698 Class II.

The small size of these rectifiers is achieved by shortening the anode to cathode spacing, which in turn reduces the arc drop to between 10 and 14 volts depending on the maximum current and peak inverse voltage. Because of the close anode to cathode spacing it has been essential to use the principle of cathode spot fixation in which the cathode spot anchors itself on to a metal surface protruding through the mercury. Anchoring the spot reduces considerably the intense vapour jets which occur with a free spot, and which can be a major cause of arc-back. The " COM-PAK " rectifiers are at present liquid-cooled to allow for maximum heat transfer from the very small volumes. This type of cooling also makes it easier to prevent the ingress of dust to insulators in such applications as a.c. traction where the rectifiers are in close proximity to the railway track.

Mobile tests, carried out in close collaboration with British Railways, have been made to assess the behaviour of " COM-PAK " rectifiers under rolling stock conditions. For these experiments two double-bogie parcel vans were used to house rectifiers and their associated equipment which included the main transformer and loading resistor. The tests included shunting at walking pace against fixed buffers, high speed runs under passenger train conditions, and runs under loose-coupled freight train conditions. Throughout the whole series of experiments the performance of the rectifiers was satisfactory, only minor modifications being made to mountings to give greater flexibility. As a further result of these tests information was obtained for the design and construction of a rocking table and this is now enabling mobile tests to be simulated on the factory test bed.

HOT CATHODE GAS-FILLED RECTIFIERS.

These rectifiers differ from the mercury arc type in having a hot cathode emitter which normally consists of an oxide coated filament. The basic process of rectification is similar to that in mercury arc rectifiers. At present there are available either mercury[6] or Xenon[7] filled grid-controlled rectifiers which have mean continuous currents of up to 15 amperes with peak inverse voltages of 1,500 volts. Both gas fillings produce arc drops of about 12 volts, with additional losses in the cathode heater of 10 watts per ampere. With the development of new types of thermionic cathodes, it is now becoming possible to make rectifiers with much larger outputs, and mean continuous currents of at least 100 amperes can be considered.

At its full rating the life of a mercury-filled rectifier is about 20,000 hours and is limited by the cathode. Xenon-filled rectifiers have operational lives of up to 10,000 hours, the limitation here being that the gas disappears over a period of time due to the clean-up effect of the arc. The main advantages of these rectifiers are that they are air-cooled, cheap to produce and occupy a very small volume. Also in the case of the Xenon rectifier a wide operating range of temperature, from −55 deg. C. to +70 deg. C., is permissible.

CONTACT RECTIFIER.

This form of rectifier was developed initially to supply very large currents for electrolytic plants where a direct voltage of up to 500 volts is required, and where the load is normally constant. At these voltages the efficiency of the contact rectifier is very high.

Rectification is obtained by the use of metal contacts in each secondary phase of the rectifier transformer. Since commutation from one phase to the next does not occur naturally, as for example in mercury arc rectifiers, the transfer of current from one phase to the next must be obtained by operating the contacts in synchronism with the supply voltage. It is essential that no contact is opened while carrying any appreciable current, otherwise severe arcing and rapid contact wear will take place. The period of zero current for any particular contact is very short, and to prevent contacts opening while carrying too much current, use is made of specially designed series reactors. These reactors have almost zero impedance at currents above a certain small value, and when the current falls below this the impedance changes to a high value, at which point the contacts are made to open. In certain designs a by-pass capacitor is fitted across the contacts as shown in fig. 4 to ensure that the contact current is actually zero during the opening period.

Arc losses are avoided by the use of the synchronously operating contacts, the losses that do occur

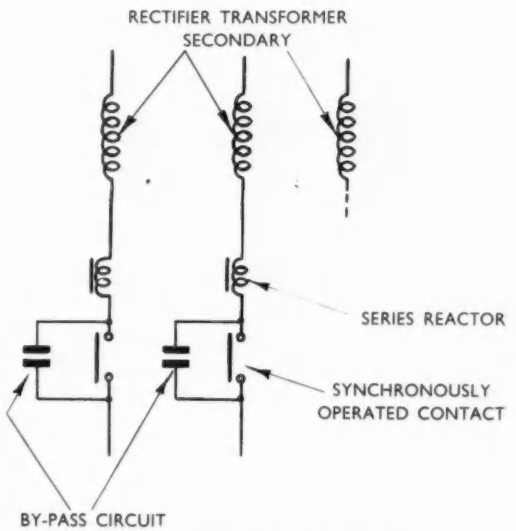


Fig. 4.—Basic circuit of contact rectifier.

being mainly in the rotating machinery. Wear and arcing of the contacts themselves limit their life to some 8,000 hours, but replacement contacts can be fitted with little trouble.

In its most modern form[8] this type of rectifier has particular application in the lower part of the voltage range because of its high efficiency at large output currents, and its reasonable size. The main disadvantages are those inherent in machines with moving parts and a rather complicated design. Moreover, contact rectifiers are not suitable for conditions where heavy peak loads occur, such as in traction or rolling mill service. This is due to the fact that the phase angle of current extinction in any particular contact varies as the load current changes. With rapid changes in load current it is impossible to alter, at the same rate, the speed of the motor driving the contacts. Consequently contacts can open when carrying current, and heavy arcing and wear will result.

SEMICONDUCTOR RECTIFIERS.

Developments in the field of solid-state physics have led to the design of a number of " solid " rectifiers, or semiconductor rectifiers. One of the first of these was the selenium type which has been in extensive use for about twenty years. However, of even greater importance now are the germanium and silicon rectifiers which have made great progress in the past five years.

In the selenium type, rectification occurs at the junction of a semiconductor and a metal. With germanium and silicon, on the other hand, rectification normally takes place at the boundary between two variants of the same material, for example, between *p*-type and *n*-type germanium.

Full accounts of the basic physics of semiconductor materials and their use as rectifiers will be found in the now extensive literature on the subject, for example [9, 10, 11].

Selenium Rectifiers.

Individual plates in selenium rectifiers can have a mean current rating of up to about 100 amperes at a peak inverse voltage of 40 volts, corresponding to a direct power rating of 2 kilowatts for a plate operating in the 3-phase bridge connection. For higher currents, plates are connected in parallel. Selenium rectifiers are usually air-cooled or oil-cooled and rated for operation in an ambient of 35 deg. C. Ambient temperatures as high as 85 deg. C. can be allowed but this necessitates substantial derating.

For rectifiers operating in the medium voltage range, series connection of plates is, of course, essential and the rectifier manufacturers supply matched plates in stacked assemblies. With these, an acceptable distribution of reverse voltage is obtained ; it is unnecessary to connect voltage dividing resistors in parallel with the plates.

With air cooling it is possible to obtain a very simple and sturdy rectifier equipment which is relatively cheap and needs no auxiliary equipment apart from a fan if forced air cooling is required. Rectifiers may be immersed in oil to give additional insulation and to provide protection against corrosive atmospheres. Improved heat conduction is also obtained with oil cooling and the current rating can be increased to two or three times the value with air cooling.

Although the overall efficiency is not high, this factor is offset to some extent by simplicity and a low initial cost, particularly at voltages in the lower part of the medium voltage range. In this range, selenium rectifiers are very suitable for the lower current applications, for example for providing power for such equipment as lifting magnets and motor drives.

Germanium and Silicon Rectifiers.

Germanium and silicon rectifiers have now established a firm foothold in the medium voltage range. The cells of both types can be air-cooled or liquid-cooled and a very robust and simple rectifier arrangement can be obtained in which no auxiliary equipment, apart from that required for cooling and protection, is necessary.

The germanium rectifier was developed before the silicon rectifier, and individual cells with mean current ratings of 100 amperes or more are now available. The higher current cells usually have a working peak inverse voltage rating of up to 100 volts.

Lower current cells with higher p.i.v. rating are available. Cells for industrial use are usually rated for operation in an ambient of 35 deg. C., but can be used at reduced power up to about 55 deg. C. The forward voltage drop in a germanium cell at its operating current is 0·5 to 0·6 volts.

The silicon rectifier also is available with mean current ratings of 100 amperes or more. It has a higher forward voltage drop (1·0 to 1·25 volts) than the germanium rectifier, but this disadvantage is more than offset in medium voltage applications by its higher peak inverse voltage rating. The working inverse voltage rating is still being steadily improved and values of 400 volts or more are seen to be feasible. The silicon rectifier can operate at a much higher junction temperature than the germanium rectifier. Consequently the current derating at high ambient temperatures is less ; useful ratings can still be obtained in ambients as high as 100 deg. C.

For both germanium and silicon rectifiers operating in the medium voltage range, it is usually necessary to connect cells in series. Since a cell would be destroyed if subjected to an excessive reverse voltage, consideration must be given to the problem of voltage distribution in series chains. Some manufacturers find it sufficient to adopt a grading scheme and rely on the fact that the reverse current will be the same through all the cells in a chain so that no cell can " run away ". Others favour the use of voltage equalising devices (for example resistors or resistors and capacitors connected in parallel with the individual cells). Sometimes more elaborate circuits are used.

When the required current is greater than can be obtained with single cells, parallel connections are necessary. It is more usual to parallel-connect series chains of cells than vice versa.

TABLE 1.

SUMMARY OF RECTIFIER CHARACTERISTICS

	Type of Rectifier				Cooling	*Typical Maximum Values for Individual Rectifier Units of		Physical Size of Complete Rectifier Equipment (excluding Main Transformer) at various d.c. Output Voltages				Inherent Overload Capacity	Ambient Temperature Range
						Mean Current (amps)	Peak† Inverse Voltage	Polyphase System			Single Phase System		
								300 volts	900 volts	3,000 volts	900 volts		
1	MERCURY ARC	Multi-Anode	Glass Bulb	Pumpless	Air	400	3,000	Very Large	Large	—	—	Medium	10 deg. C. to 40 deg. C. Up to 55 deg. C. with derating.
2			Steel Tank	Pumpless	Air	1,500	6,000	Very Large	Large	—	—	High	
3			Steel Tank	Continuously Pumped	Air	3,000	6,000	Very Large	Large	Medium	—	High	
4		Single-Anode	Ignitron	Pumpless	Liquid	750	6,000	Medium	Small	Very Small	Small	High	
5				Continuously Pumped	Liquid	750	6,000	Large	Medium	Small		High	
6			Excitron	Pumpless	Air	500	6,000	Large	Medium	Small	Medium	High	
7				Continuously Pumped	Air or Liquid	750	6,000	Large	Medium	Small		High	
8			COM-PAK Excitron	Pumpless	Liquid	300	3,000	Medium	Small	Very Small	Small	High	
9	Hot Cathode Gas-Filled		Mercury	Pumpless	Air	15	1,500	Medium	Small	—	Small	Medium	10 deg. C. to 55 deg. C.
10			Xenon	Pumpless	Air	15	1,500	Medium	Small	—	Small	Medium	−55 deg. C. to +70 deg. C.
11	Contact				Air	15,000	1,000	Medium	—	—	—	Low	
12	SEMICONDUCTOR		Selenium		Air	100	40	Large	Large	Large	Large	Medium (Life may be shortened if overloading is frequent.)	Up to 35 deg. C. with normal loading; up to 85 deg. C. with substantial derating.
13			Germanium		Air	200	100	Medium	Medium	Medium	Medium	Low (Correct circuit design and overload protection enables this problem to be dealt with successfully.)	Up to 35 deg. C. with normal loads
14					Liquid	500	100	Small	Small	Small	Medium		Up to 55 deg. C. with substantial derating.
15			Silicon		Air	150	400	Small	Small	Small	Small	Low (Correct circuit design and overload protection enables this problem to be dealt with successfully.)	Up to 35 deg. C. with normal loads
16					Liquid	250	400	Very Small	Very Small	Very Small	Very Small		Up to 100 deg. C. with substantial derating.

* These are commonly found figures. There will be considerable variation in values between indiv

† Normal working values, not absolute maxima.

CTERISTICS

Ambient Temperature Range	Auxiliary Equipment (excluding cooling)	Maintenance	Inherent Voltage Control Properties	Warming-up Time	Limitations to Way Rectifier Transformer can be connected
10 deg. C. to 40 deg. C.	Auxiliary Anode Supply	Small	Grid	None (Unless air temperature is low.)	Bridge Connections not possible because of common cathode
	Auxiliary Anode Supply	Small	Grid		
	Auxiliary Anode Supply Vacuum Pump Supply	Medium	Grid		
	Auxiliary Anode Supply Ignitron Supply	Small	Grid		None
Up to 55 deg. C. with derating.	Auxiliary Anode Supply Ignitron Supply Vacuum Pump Supply	Medium	Grid		None
	Auxiliary Anode Supply	Small	Grid		None
	Auxiliary Anode Supply Vacuum Pump Supply	Medium	Grid		None
	Auxiliary Anode Supply	Small	Grid		None
10 deg. C. to 55 deg. C.	Heater Transformer	Small	Grid	10 minutes	None
−55 deg. C. to +70 deg. C.	Heater Transformer	Small	Grid	30 seconds	None
	None	Large	Displacement of Stator of Synchronous Motor	None	None
Up to 35 deg. C. with normal loading; up to 85 deg. C. with substantial derating.	None	Small	None	None	None
Up to 35 deg. C. with normal loads Up to 55 deg. C. with substantial derating.	None	Small	None	None	None
Up to 35 deg. C. with normal loads Up to 100 deg. C. with substantial derating.	None	Small	*p-n-p-n* Structure	None	None

es between individual manufacturers.

Because of its higher peak inverse voltage rating and higher operating temperature, the silicon rectifier has greater potentialities than the germanium rectifier in the medium voltage range. Fewer cells are required in series and a simpler cooling system can be employed, hence the rectifier is more compact and, in general, more efficient. As further improvements are made in its reverse voltage rating, the silicon rectifier will compete increasingly strongly with the mercury arc rectifier.

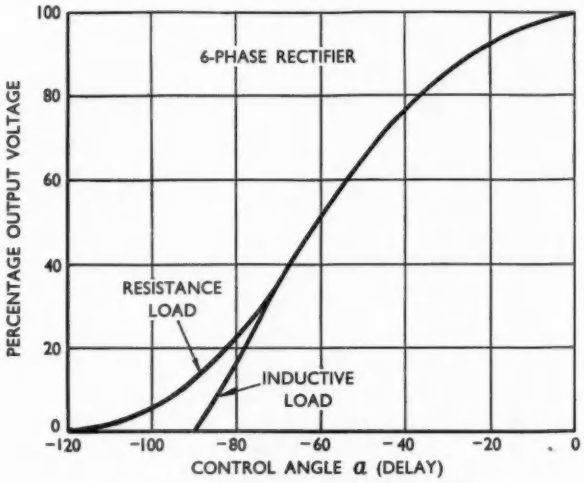


Fig. 6.—Output voltage as a function of control angle.

GRID CONTROL.

In the mercury arc and hot cathode gas-filled rectifiers it is possible to interpose a grid between the main anode and the cathode. This grid prevents the anode with which it is associated from carrying current until it is required to do so. By applying to the grid a voltage which is negative with respect to the cathode, the anode can be prevented from conducting; when the grid is made sufficiently positive the anode will conduct as soon as it is itself positive with respect to the cathode. By altering the phase angle of the positive grid signal with respect to the main anode voltage it is possible to vary the direct voltage output from its full value to zero. Fig. 6 shows the output voltage as a function of control angle. Details of circuits for the static control of single- and multi-anode rectifiers have already been published in this Journal.[12]

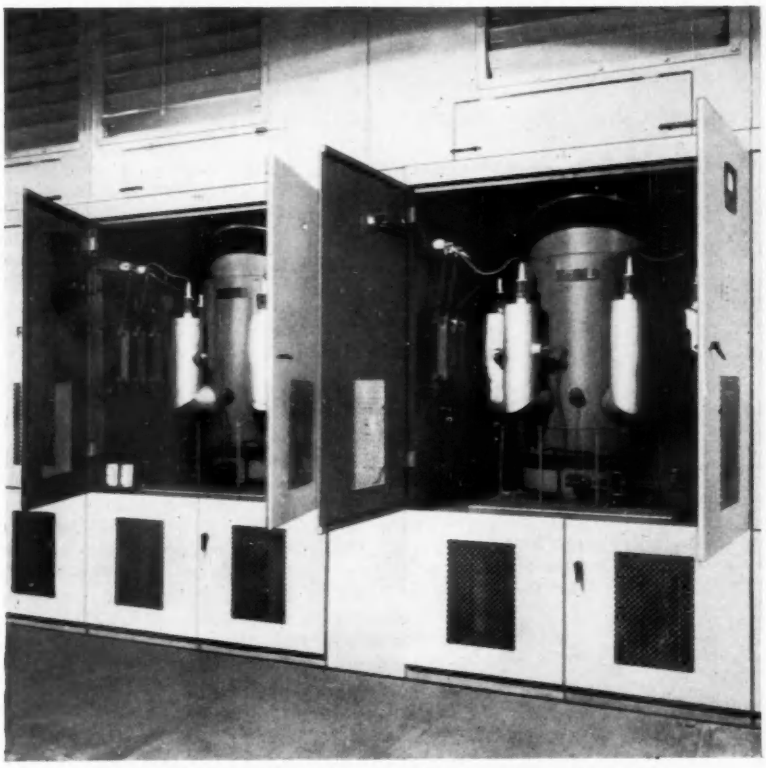


Fig. 5.—G.E.C. 850 volt, 1,260 amp, multi-anode, grid-controlled rectifiers.

The amount of power required in the grid circuit is only a few watts. This low-power system, which can be made very fast acting, is capable of controlling very large output powers. It is thus ideal for such applications as the control of large d.c. motor drives in steel plants, automatic control of voltage and current in printing press drives, and the control of processes where very rapid changes in voltage and current are demanded. These rapid changes would not be possible with most normal forms of a.c. regulation on the primary side of the rectifier transformer. In the grid-controlled rectifier equipment shown in fig. 8, single-anode excitrons are used, the variable voltage supply controlling a printing press drive. The use of the grid control also reduces the volume of the voltage regulation equipment to almost negligible proportions, com-

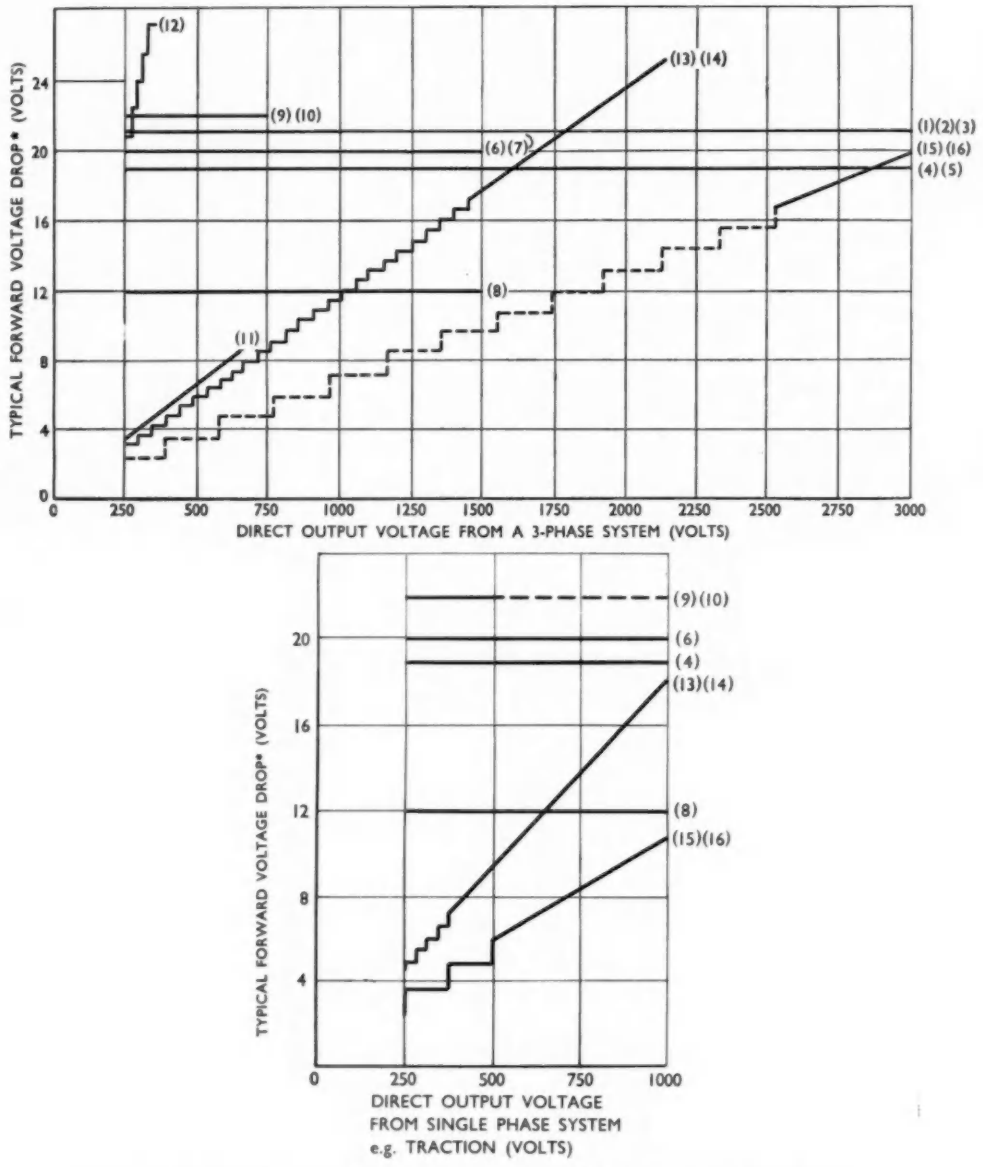


Fig. 7.—Relative efficiencies of various types of rectifiers under single- and 3-phase conditions.
(*The forward voltage drop includes auxiliary supplies in mercury arc rectifiers and heater losses in gas-filled hot-cathode rectifiers.)

(1) M.A. Glass Bulb.
(2) M.A. Steel Tank (pumpless).
(3) M.A. Steel Tank (continuously pumped).
(4) M.A. Ignitron (pumpless).
(5) M.A. Ignitron (continuously pumped).
(6) M.A. Excitron (pumpless).
(7) M.A. Excitron (continuously pumped).
(8) M.A. " COM-PAK " Excitron (pumpless).
(9) Gas-filled, hot-cathode (Mercury).
(10) Gas-filled, hot-cathode (Xenon).
(11) Contact.
(12) Selenium (air-cooled) — 1·5 volts forward, 40 volts P.I.V.
(13) Germanium (air-cooled) — 0·55 volts forward, 100 volts P.I.V.
(14) Germanium (water-cooled) — 0·55 volts forward, 100 volts P.I.V.
(15) Silicon (air-cooled) — 1·2 volts forward, 400 volts P.I.V.
(16) Silicon (water-cooled) — 1·2 volts forward, 400 volts P.I.V.

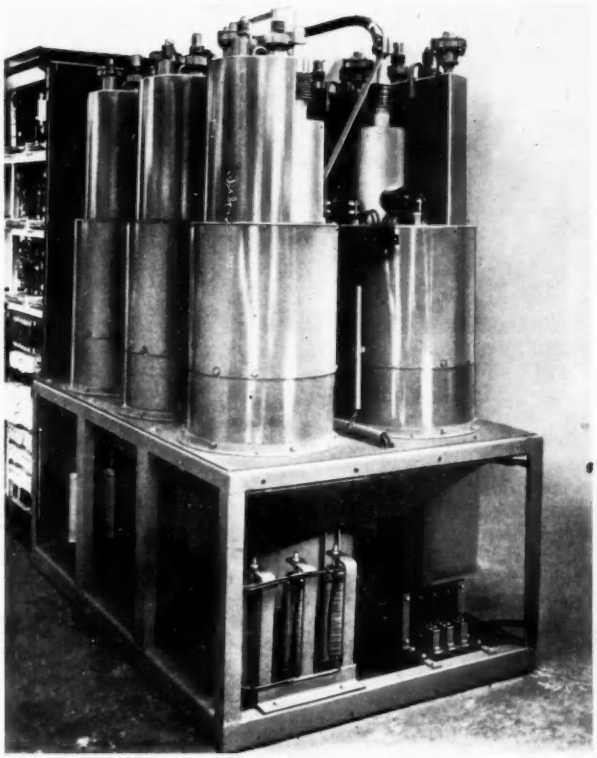


Fig. 8.—G.E.C. grid-controlled rectifier for controlling a printing press drive.

pared with such equipment as induction regulators.

A secondary use of grids is their blocking capacity. This can help considerably in switching operations and is a quick and easy way of applying or removing the output voltage. It is also possible by means of a simple saturated transformer to allow a heavy negative bias to be applied to a grid should a fault occur in the rectifier system. This bias prevents conduction of all the anodes until the fault condition has been removed.

CONCLUSIONS.

An attempt is made in Table 1 to summarise the main characteristics of the rectifiers described in this article. Fig. 7 shows their relative efficiencies as a function of direct output voltage.

In the field of straight rectification, where a non-variable output voltage is required, germanium and silicon rectifiers are beginning to challenge the position of the mercury arc rectifier which has hitherto successfully dominated the medium voltage field. This is particularly so at output voltages below about 750 volts. It is also doubtful whether the contact rectifier, which has given good service in the post-war period, particularly on the continent, will survive for very long the competition from semiconductor rectifiers.

Where a variable direct output voltage is required, particularly one of high speed response, the grid-controlled rectifier is likely to be the solution for some years ahead. However, for this type of application also, there are new semiconductor devices which may eventually present a challenge to the conventional grid-controlled rectifier. These new devices are the controlled solid rectifiers using a *p-n-p-n* structure.[13] Thus, it is evident that many interesting developments lie ahead in the rectifier field.

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Contact Welding in Thermostats

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INTRODUCTION.

IN industrial and domestic installations, temperature control of heating appliances other than the electric fire is in common use. In large industrial heating plants the thermostat usually operates indirectly through switchgear, but in the domestic application it is required to perform the switching duties directly, when operating in a.c. circuits. In this case the thermostat contacts have a more arduous duty and, since their performance directly governs the effectiveness of the temperature control, their capabilities must be known. Before the use of switching thermostats it was customary to design domestic appliances so that, with their heaters continuously energised, the heat input was balanced by the heat losses at the maximum temperature required. Since the acceptance of thermostatic control the power of heaters has tended to increase; for example, the heating element of a modern cooking oven operating at the top temperature setting (usually 550 deg. F.) will be switched on for only about one-third of the time. The increase in power gives a shorter time for heating from cold, but increases the electrical loading of the thermostat. It also renders more catastrophic any failure of the thermostat to open the circuit. The modern King Alfred would pass the blame on to the thermostat and nobody but the thermostat manufacturer would question his judgment. If the thermostat contacts weld together in operation, the thermostat may not open the circuit until too high a temperature has been reached. It is necessary, therefore, to have some assessment of the likelihood of contacts welding and of the forces needed to break such welds. The purpose of this article is to present some results of an experimental investigation of this factor in contact performance.

There is nothing new, or indeed difficult, about temperature control considered as a problem in itself. Roosevelt Griffiths's book,[1] first published in 1934, gives a comprehensive survey of the physical principles involved. The difficulties arise when it is required to produce thermostats in quantity, cheaply. The market for domestic appliances is competitive, and a fine balance has to be struck between price, accuracy, reliability and long life.

Most thermostats consist essentially of three parts: a temperature-responsive element which on change of temperature produces a mechanical movement, a switch to make and break the heating circuit in response to the mechanical movement, and a linkage between the two. The linkage may be required to perform several functions, e.g. to amplify the mechanical movement obtained from the temperature-responsive element, or to facilitate adjustment of the relative position of the other two parts to effect changes in setting. Thermostats used for the control of domestic equipment usually incorporate switches capable of handling the full electrical load of up to 20 amperes at normal supply voltage without the use of relays or contactors. Thermostat switches are generally quick-make and quick-break in operation, requiring an appreciable mechanical movement of the operating member between the make and break actions. Because of this there is a temperature interval between the two switch operations, known as the " differential " of the thermostat. In most thermostats there is at least one resilient part which, by its deflection, can absorb strain energy as the force on the switch is built up. Bimetal strip, when used as the temperature-sensitive member, provides its own spring properties, but with expanding liquid or tube and rod operations it is necessary to provide some resilience in the linkage between the thermal operator and the switch. This prevents damage to the switch when the thermostat is reset to control at a lower temperature.

In order to provide reasonably close control, with differentials of 10 deg. F. to 20 deg. F., for example with water heater and cooker controls, switches of the micro-gap type are used. These have gaps of about 0·01 in. between the contacts when in the open position and when operating on a.c. rely on the arc at break being extinguished at the following current zero. This type of switch is not recommended for direct control on d.c.

A micro-gap switch operates consistently when breaking light current loads and requires a well-defined force to open the contacts. As the current is increased it is found that the opening force becomes more variable, and much higher values are occasionally needed. This variability in force is due to the switch contacts welding together and, through the mechanism described, gives rise to variability in the control temperature. From consideration of the use of any particular type of thermostat a reasonable limit to the permissible excess temperature can be fixed. For example, with a water heater thermostat the difference between the top setting temperature and the boiling point of water fixes an extreme limit. The thermostat designer therefore needs to know the strength of contact welds likely to be encountered with the electrical duty proposed for the thermostat. Knowing this he

can design a thermal and mechanical system to provide the contact opening force required to ensure that the thermostat will perform within reasonable limits of excess temperature.

WELDING MEASUREMENTS WITH A.S.T.M.-TYPE MACHINE.

Apparatus for the measurement of contact welding has been designed by the American Society for the Testing of Materials.[2] A form of this equipment, used at the Research Laboratories, is shown diagrammatically in fig. 1. The contacts, which are $\frac{3}{16}$ in. diameter discs some 0·03 in. thick, mounted on No. 4 B.A. brass screws, are closed by the spring A. The separating or pull-off force is adjustable by the spring B and once set is applied to the contacts periodically once per second by the rotation of the cam. When the contacts weld together with a strength greater than the set pull-off force, that is if the contacts are not separated by the first application of the pull-off force, control circuits interrupt the contact load current and energise the solenoid C. This prevents further application of the pull-off force and an attendant may come and measure the strength of the weld with a spring balance. In the experiments to be described the closing force is 15 grammes, the speed of the moving contact at closing is 1·5 in./sec. and the voltage in the contact circuit is 270 r.m.s., 50 c/s. The pull-off force is generally set to 65 grammes and welds weaker than this are not detected. Six pairs of contacts are operated in sequence from a common camshaft and the test is generally run for 100,000 operations. This compares, for example, with the specified life test for a water heater thermostat (B.S. 1555), which is 50,000 operations.

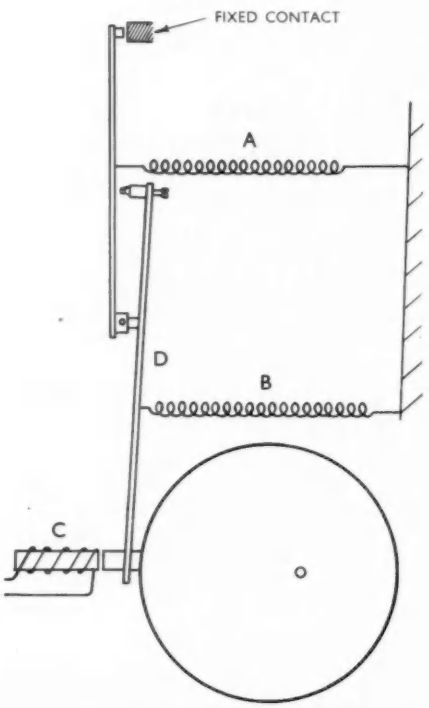

Fig. 1.—A.S.T.M.-type contact testing machine.

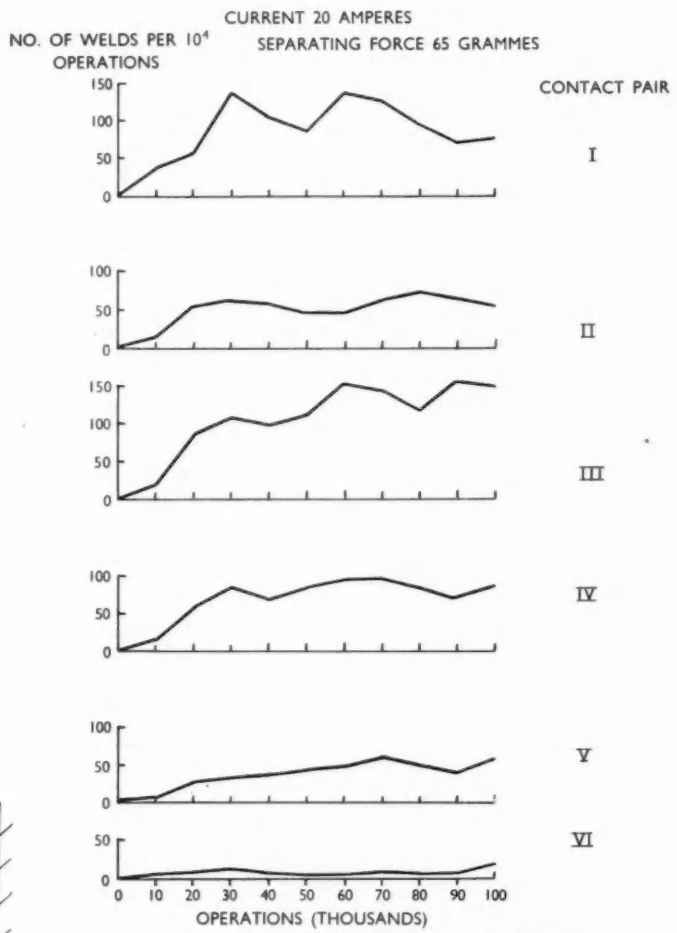

Fig. 2.—Variation of welding incidence with life.

Fine-silver contacts with loads of 15 and 20 amperes at unity power factor weld together with strengths which require breaking forces of up to 70 and 150 grammes respectively. Fig. 2 shows the rate of welding during a test at 20 amperes with fine-silver contacts. Each point on the graph indicates the number of welds counted in the previous 10,000 operations. It will be

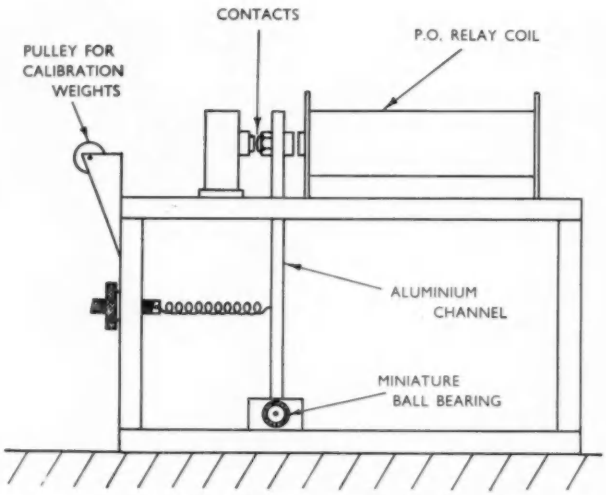

Fig. 3.—Electro-magnetic contact testing apparatus.

noted that there is some difference between the behaviour of the different contacts and this is not related to any of the measured characteristics, e.g. bounce or speed.

By a rearrangement of the apparatus it is possible to control three electrical loads with six pairs of contacts in such a way that, on each load, one pair of contacts closes after the other, thereby making the circuit, and the other pair opens first, thus breaking the circuit. The total number of welds observed with this arrangement is about one-eighth of that observed when each contact both makes and breaks the circuit. This suggests that the disturbance of the contact surface at break caused by the arc and bridge phenomena, has a considerable effect on the liability of the contacts to weld. Also, it is found that the break contacts weld, though less frequently than the make contacts. It has not been determined whether the welding of the break contacts occurs during the breaking operation or when current first passes through these contacts when the make contacts close.

Effect of Inductance.

The effect of reducing the power factor of the load to 0·5 lagging, with each contact both making and breaking, is to reduce the number of welds to about one-seventh of that occurring at unity power factor. With make and break carried out by separate contacts, it is found at the reduced power factor that welds only occur at the break contacts and the number observed is not significantly different from that with both make and break performed by the same contacts at this power factor.

Distribution of Welds According to their Strength.

While the results quoted above give an introduction to the contact welding problem in thermostats and similar contact applications, much information is lacking. In particular, the arbitrary definition of a weld as a refusal of the contacts to open under the influence of a set force is unsatisfactory.

A testing apparatus which allows all welds and their strengths to be recorded is shown in fig. 3. The contacts under test are closed by a helical spring which is adjustable to determine the contact closing force. The contacts are opened by an electro-magnet which is periodically energised by a timing system. A magnetic clutch, energised at the same time as the electro-magnet, connects the slider spindle of a toroidal rheostat to a continually rotating shaft. The rheostat is in series with the electro-magnet and, when its slider is driven, the solenoid current is increased. When the pull of the electro-magnet exceeds the combined contact weld strength and closing force, the contacts open and, by means of a relay, the clutch is de-energised. A spring returns the rheostat slider to the high resistance position, reducing the electro-magnet current to a value just sufficient to hold the contacts open. When the timer initiates the next cycle, the electro-magnet current is interrupted and the contacts close under the action of the spring. The speed of travel of the contact arm is regulated by an oil dashpot. The current in the electro-magnet is recorded on the chart of a recording milliammeter, the chart being moved one step for each operation. Fig. 4 is a typical trace. The apparatus is calibrated by tests carried out with weights hung on the contact arm and a very small current in the contact circuit. Six machines are run at the same time and the procedure is to record weld strengths for 1,000 operations on each of them at intervals in a run of 100,000 operations. Fig. 5 is the distribution of average numbers of welds obtained from the six machines working with a load of 20

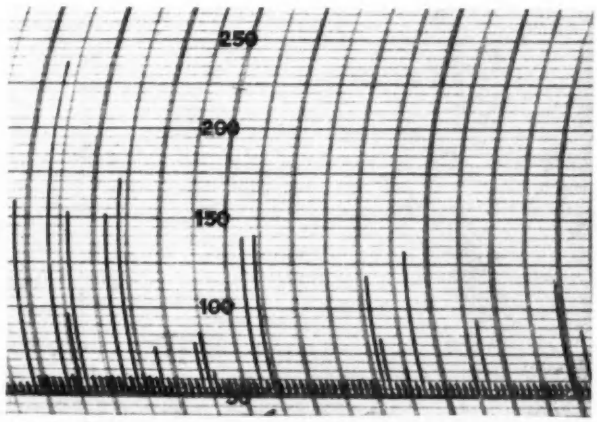

Fig. 4.—Electro-magnetic contact tester; chart showing contact closing force (short traces) and weld strength (long traces).

amperes, 270 volts r.m.s. and power factor 1·0. The speed of the moving contact just before closing was 1·5 in./sec.

Counting the numbers of welds of 60 grammes and over it is seen that there are about six times as many as were obtained with the old machine with a similar load. This is due presumably to the more gradual application of the pull-off force giving rise to less shock and vibration. The maximum weld strengths are also higher by 50 grammes or so than those obtained on the other apparatus.

Tests have also been made with this apparatus with other contact materials. Some of these materials have been recommended from time to time for having a reduced tendency to weld, but the results given in Table 1 indicate that silver-cadmium oxide and silver-graphite have no advantage over fine-silver in the range of forces encountered in thermostats.

A test has also been made with fine-silver contacts with a contact speed at closing of 6 in./sec. In this case, an attempt was made to produce a similar pattern of bouncing to that obtained at the lower

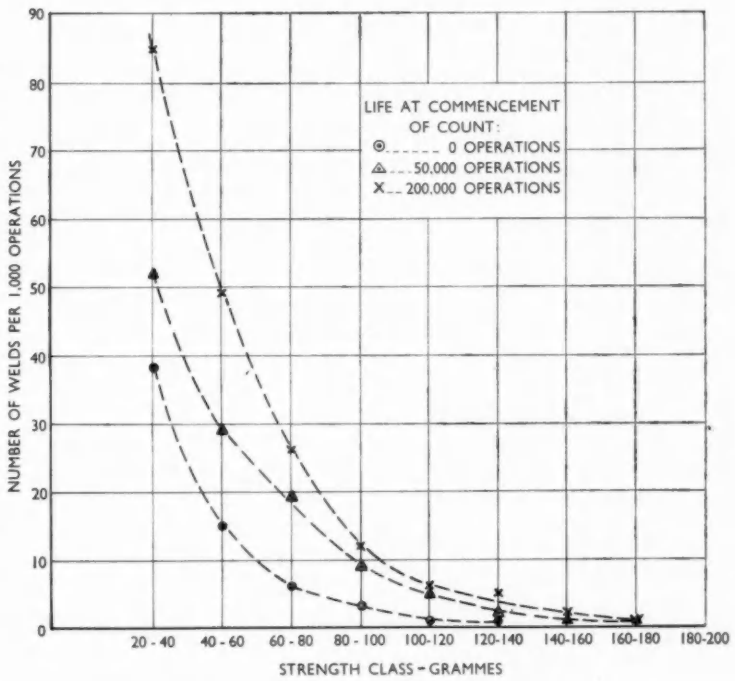

Fig. 5.—Average weld strength distribution for fine-silver contacts. 20 amp. r.m.s., unity power factor, speed at closing 1·5 in./sec.

TABLE 1.

NUMBER OF WELDS PER 1,000 OPERATIONS AFTER 100,000 OPERATIONS. CURRENT 20 AMPERES, 270 VOLTS r.m.s., SPEED 1·5. in/sec.

Average of 6 tests

Weld Strength Grammes	Fine Silver	Fine Gold	Pure Palladium	Silver Cadmium Oxide	Silver Graphite
20– 40	63	75	184	77	72
40– 60	38	45	92	57	63
60– 80	22	23	52	40	41
80–100	10	13	26	26	32
100–120	6	8	14	16	24
120–140	2	4	6	9	17
140–160	2	3	3	5	11
160–180	1	2	2	2	6
180–200	1	1	1	2	2
>200	1	—	—	—	6

Figures in the table are from smooth curves drawn through graphs of experimental results. The results plotted are the averages obtained from six test machines operating at the same time.

speed. Three of the contact machines were fitted with bounce suppressors, the fixed contact being mounted at the centre of a copper leaf spring anchored at its ends. A small box partly filled with magnesia powder was fixed to the back of the contact, a method of reducing bounce mentioned by Holm.[3] The effectiveness of the bounce reduction may be judged from the oscillograms in fig. 6 and 7. Fig. 8 shows the effect of this on the welding distribution. The reduction of welding with the rearrangement of the fixed contact may be due, in part, to the greater flexibility of the mounting, which may have introduced shearing forces. The mounting of the contact at the centre of the spring leaf should minimise this effect. The indication from fig. 8, compared with fig. 5, is that if bouncing can be kept to a similar pattern the increase in speed of travel at closing reduces welding.

DISCUSSION.

In order to produce a weld between contacts, energy must be dissipated in the contact interface to melt the metal. E. I. Shobert[4] has suggested that this may be estimated by assuming that the weld is of circular cross-section and finding the heat required to raise to melting point the temperature of a sphere of metal, of which the weld is an equatorial plane. The area of the weld may be estimated from its strength and the breaking stress of the material. Then, using this information, the energy required to make a 100 gramme weld in silver is estimated to be about half a millijoule.

There is also a well-known relationship between the maximum temperature in a contact interface and the potential drop across it.[5] Clearly, for a weld to occur, a pulse of energy is required at the conclusion of which the potential drop across the contact must be not less

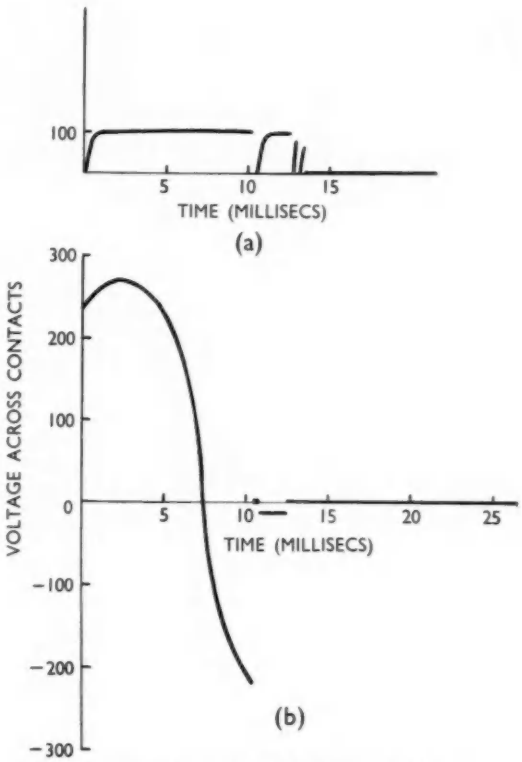

Fig. 7.—Bouncing of contacts with closing speed of 1·5 in./sec.
(a) Small direct current. (b) 20 amp. a.c.

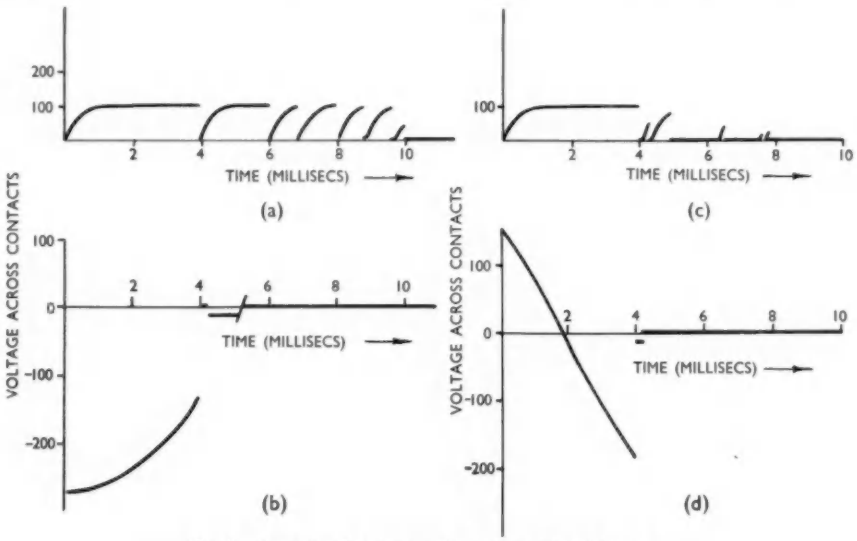

Fig. 6.—Bouncing of contacts with closing speed of 6 in./sec.
(a) Small d.c., no suppressor. (c) Small d.c., with bounce suppressor.
(b) 20 amp. a.c., no suppressor. (d) 20 amp. a.c., with suppressor.

TABLE 2.

PROBABILITY OF OCCURRENCE OF WELDS.

5 contacts each performed 10 runs of 2,000 operations with a 20 ampere load at unity power factor—50 "tests" in all.

Number of Welds per test	0	1	2	3	4	5
Number of tests, actual	10	13	13	8	4	2
Number of tests, Poisson	8·4	15·0	13·3	7·9	3·5	1·2

than that corresponding to the melting temperature of the metal. For silver the voltage is 0·35, about ten times the potential drop across thermostat contacts under steady conditions.

E. and R. Holm[6] have considered these criteria in a theory of welding for electrodes held in contact, the contact closing force being applied before the current was switched on. In the present case, an estimate of the energy dissipated at the contact interface during closing requires a knowledge of the form of the resistance-time curve. The early results of experimental determinations of this indicate that the duration of the transient resistance period is about 10 microseconds. It is interesting to note that, in the apparatus described, a reduction of the power factor to 0·5 eliminates welding at make and also introduces a delay in the rise of current at make of about this duration. The inductance in the circuit ensures that the contact resistance is down to its steady value before there is any significant flow of current across the contact interface.

The evidence, therefore, points to Joule heating at the contact surface at make being the main source of energy for contact welding. There are also other factors affecting the contact which superimpose a probability factor on the simple condition of energy available. For example, it was found that at 15 amperes r.m.s. the strongest welds were of 70 grammes strength. If the mechanism of welding is as described one would expect, with unity power factor, the strongest weld to occur when the contacts closed near to the voltage peak. With 20 amperes r.m.s. there is a 46 per cent probability of the contacts closing at a point on the voltage curve giving an initial current of $15\sqrt{2}$ amperes or greater. This would lead to 46,000 chances of a weld of 70 grammes or more in 100,000 operations with a 20 ampere load. In fact the number of welds in such a run is found to be 750, or $1\frac{1}{2}$ per cent of that expected. The probability of contact welding under these conditions is found to follow a Poisson distribution quite closely, as is shown in Table 2. The effect of bouncing, quite apart from any arc phenomena, is to increase the number of actual makes by the number of bounces and so increase the probability of welding.

Much more detailed study of the transient resistance when the contacts come together and of the mechanical factors of contact operation is required in order to explain the observed incidence of welding.

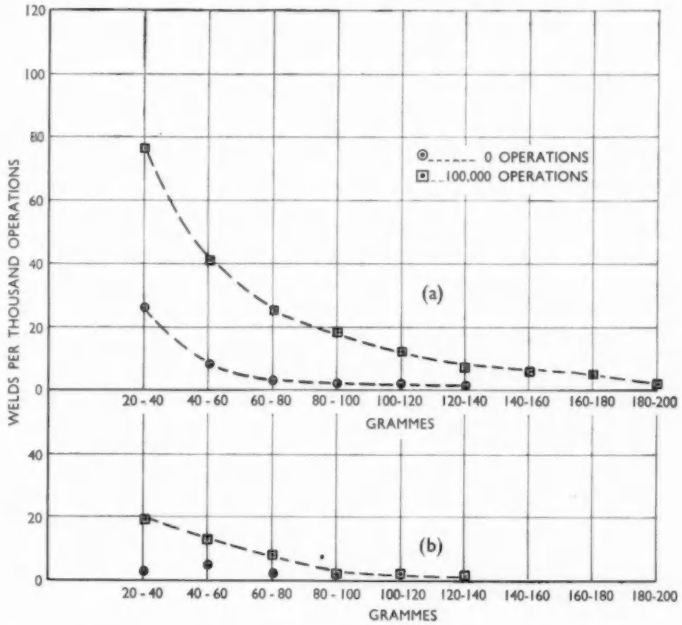

Fig. 8.—Average weld strength distribution for fine-silver contacts. 20 amp. r.m.s., unity power factor, speed at closing 6 in./sec.

(a) average of three contacts without bounce suppressors.
(b) average of three contacts with bounce suppressors.

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Winding Plant for Lea Hall Colliery

By L. G. BOTEVYLE, Engineering Group, Erith,
and C. A. MAER, Engineering Group, Witton.

PRIOR to 1949 it was thought that coal measures to the east of the Eastern Boundary Fault of the Cannock Chase Coalfield were non-existent or of little value. In that year, however, boreholes revealed the presence of a full series of coal measures similar to those found in the southern part of the Cannock Chase Coalfield. Rapid and extensive proving of the new field followed and culminated in the decision to build a completely new colliery, which will be the first of such projects to be initiated and executed solely by the National Coal Board.

For some time previously the Central Electricity Authority, now the Central Electricity Generating Board, had been contemplating the construction of a 600 MW power station on the banks of the River Trent in the same vicinity. As soon as the probability of the development of a colliery became apparent, the planning staffs of the two nationalised bodies worked together, resulting in arrangements for the direct supply of the bulk of the fuel requirements to what will be one of the major generating stations in the Midlands.

The initial contract for winding plant was awarded to the G.E.C. and covered two 3·3 kV geared a.c. cage winding engines of 2,100 h.p. each, one for the upcast and one for the downcast shaft. Both shafts were arranged so that a second winder could be installed at each to handle the increased output of the colliery in the final stage of development. A subsequent order covered a second single-drum winder for the downcast shaft, and this is now being manufactured.

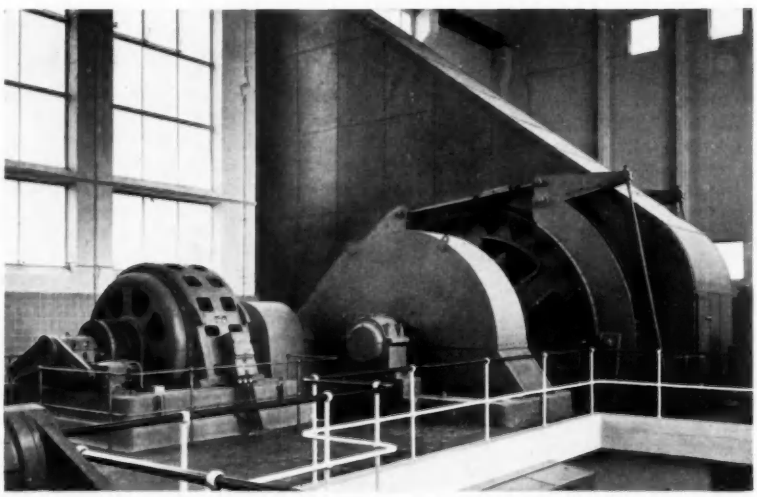

Fig. 1.—2,100 h.p. single-drum a.c. winder for the downcast shaft.

MECHANICAL EQUIPMENT OF UPCAST WINDER.

At the upcast shaft of the colliery the winder is of the double-drum type to enable winding to be carried out from three levels. The theoretical duty cycle diagram for the maximum depth is shown in fig. 2, and the equipment is designed for an output of 250 tons of coal per hour when winding from 1,732 ft. Each drum is 16 ft. in diameter at the rope centres

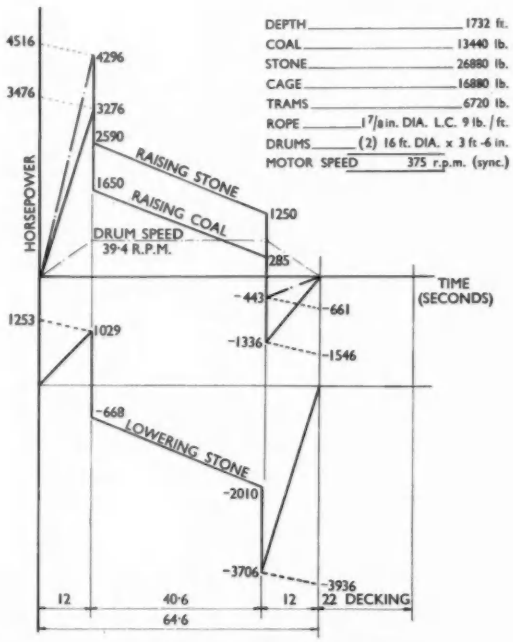

Fig. 2.—Duty cycle for upcast shaft.

and 3 ft. 6 in. wide between flanges. One drum is fixed to the shaft, the other being driven through a multiple-tooth clutch. The clutch teeth are generated over the full circumference of the driving member and give a minimum rope adjustment of 6 in. The clutch, which can be seen in fig. 3, is operated by an hydraulic cylinder mounted on the outer soleplate, the cylinder being controlled by a lever on the driver's desk. Hydraulic interlocks are provided to ensure that the brake is fully applied to the loose drum before the clutch is withdrawn, and conversely mechanical interlocks ensure that the brake is not released until the clutch is fully engaged.

The drums are arranged for double-layer coiling of the winding ropes at maximum depth, and spare rope for re-capping is carried on the drum barrel as extra dead coils. The grooving for the ropes is of interest as it is of the spiral/parallel type. With this type of grooving, which has been developed at the Company's Erith Works, the ropes, when coiling on the first layer, run in a continuous groove, but when coiling on the second layer they have one cross-over point only. The advantages of both the normal spiral and the parallel types of groove are therefore obtained without their respective disadvantages. Due to the tandem-mounted headsheaves and consequent adverse rope lead, rope risers and kicking plates are provided at the points where the ropes rise from the first to the second layer. Positioning of the risers and kicking plates was made after the ropes had been installed and tensioned.

The drums are driven by the 2,100 h.p. motor through single-reduction splash-lubricated double-helical gears with a ratio of 9·05 : 1. The gear wheel is of fabricated construction and is cut with hobbed continuous-type teeth. The pinion is forged integral with its shaft from high-carbon steel, and the drive is transmitted from the motor to the pinion through a flexible spring coupling. The bearings supporting both the main drumshaft and the pinionshaft have self-aligning cast-steel bushes, lined with white metal, and are fitted with twin oil rings. Seals are provided to exclude dust and other foreign matter.

The auxiliary equipment includes a vertical twin-screw depth indicator incorporating, at the base, power lever returning cams for the end of the wind. A loose-dial duplex Lilly controller, type "C", gives full protection against overwind and overspeed at any point during the wind. In either of these contingencies the controller interrupts a safety circuit which causes the emergency-brake solenoid to be de-energised, thus applying the mechanical brakes.

Braking System.

The mechanical brakes are of the centre-suspended parallel-motion type and have shoes that are machined on their faces to receive the woven asbestos friction lining. Manual and emergency application is effected by the well-proved low-pressure type brake engine and operating equipment shown diagrammatically in fig. 4. The pressure service engine consists essentially of a two-diameter cylinder fitted with a two-diameter piston, the larger diameter being at the lower end. Constant-pressure oil at approximately 100 lb./sq. in. is supplied to the top of the cylinder, and the pressure

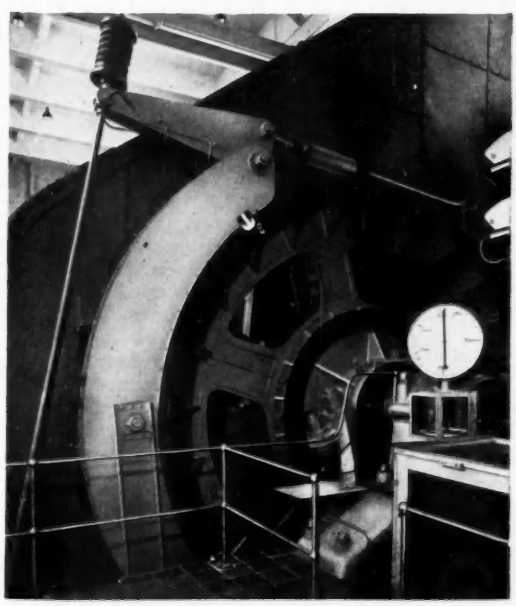

Fig. 3.—Mechanical brake and clutch of upcast winder.

in the bottom of the cylinder is controlled by the main brake valve and pressure regulator.

With the driver's brake lever in the "off" position, as shown, the oil pressure on both sides of the piston is the same, and the piston, because of the larger area at its lower end, is maintained in a raised position, thus holding off the brake shoes. Movement of the driver's lever to the "on" position opens the main brake valve and exhausts the oil from below the piston. The constant pressure on the top brings the shoes into contact with the brake paths and maximum braking torque is developed.

The pressure under the piston is governed by a pressure regulator, which makes it possible to obtain a variation in the braking torque from zero to maximum over the complete range of movement of the driver's brake lever. The amount of braking applied is at all times directly proportional to the position of the lever irrespective of any wear on the friction linings.

In the event of an emergency trip initiated by one of the devices in the safety circuit, the emergency solenoid is de-energised. This causes the main brake valve to open and exhaust oil from the underside of the brake engine piston, thus applying the brakes. An adjustable stop controls the distance moved by the emergency solenoid, and this, in conjunction with the pressure regulator, enables the braking torque applied under emergency conditions to be reduced, if required, from the maximum torque available by movement of the driver's brake lever.

An adjustable relief valve controls the working pressure of the hydraulic system, and hence the maximum braking torque can be set to give the required retardation. When winding at high speeds, the rate of application of the mechanical brakes is controlled by a slow-brake valve. This restricts the flow of oil from the brake engine at high speeds, but ensures rapid application of the brakes when the winding speed falls.

To provide an adequate reserve of pressure oil for operation of the brakes an air/oil accumulator is installed. This has capacity for some twelve or more strokes of the pressure service brake engine and its purpose is to enable the conveyances to be landed safely, under gravity, in the event of a complete power failure. It therefore eliminates the likelihood of men being trapped in the shaft, possibly for some considerable time.

The air/oil accumulator consists of an air receiver into the bottom of which oil is pumped to a predetermined level. The receiver is then charged by an air compressor to the working pressure of the system. Under normal conditions, subsequent operation of the compressor occurs only if large quantities of air are absorbed by the oil, causing the oil level to rise and operate a magnetic level switch. The switch starts the compressor and the oil is forced out of the receiver through a relief valve to the sump. When the oil in the receiver has fallen to the predetermined level, the air compressor is cut out by the level switch, so that the

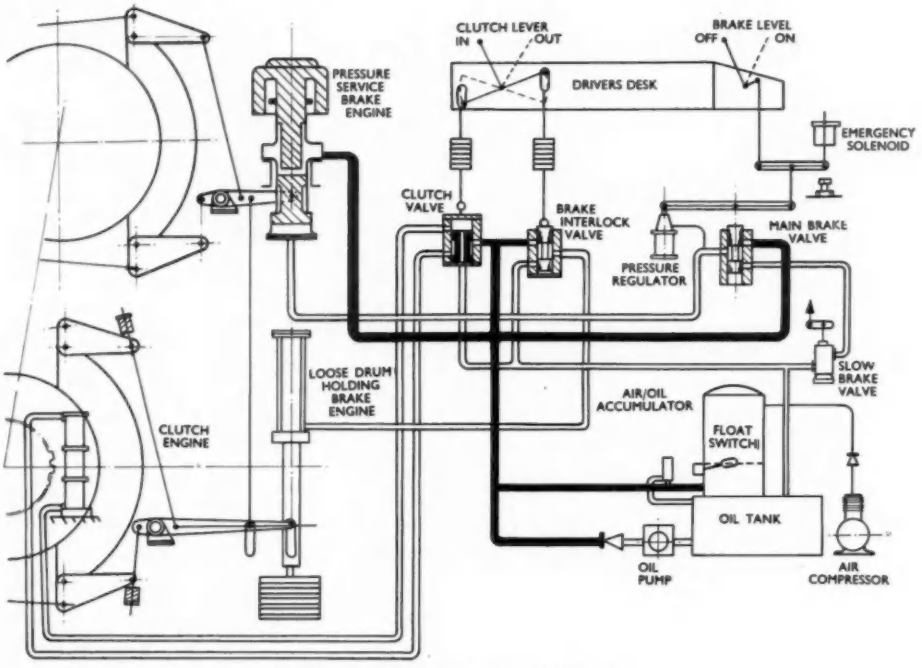

Fig. 4.—Schematic diagram of braking system.

accumulator capacity is maintained automatically. The magnetic level switch is so constructed that there is no mechanical connection between the float and the switch contacts, and hence leakage of air cannot occur at that point. The switch is also fitted with a device that allows the oil level to rise about six inches above normal before the compressor is started, thereby preventing too frequent topping-up of the accumulator.

The accumulator was specially developed to operate with the pressure type brake engine. With a normal dead-weight type of accumulator, the weight may drop when the brakes are applied rapidly. The inertia effect would then be transmitted to the brake engine and so defeat its purpose, which is to eliminate large moving weights. The brake engine is fitted with a weight system, but this is normally supported by the constant pressure oil. In the event of a sudden failure of pressure, due, for instance, to a broken pipe, the weight falls and applies the brakes.

Clutch Operation.

To change levels the loose-drum conveyance is brought to the pit top and the brakes are applied. The driver then moves the clutch lever to the "out" position. This instantly operates the brake interlock valve, causing oil to flow from the underside of a standard weight-type brake engine which applies the brake associated with the loose drum. Further movement of the lever operates the clutch valve, which allows the oil to flow to the underside of the clutch engine and opens the top to exhaust, thus disengaging the clutch. The new level is then selected, the pressure brake being operated from the driver's brake lever in the normal manner, while the loose-drum conveyance is held at the top of the shaft.

When the driver re-engages the clutch, movement of the lever to the "in" position allows oil to flow to the top of the clutch engine and opens the underside to exhaust.

THE DOWNCAST WINDER.

The winding engine at the downcast shaft is of the single-drum type and is capable of an output of 280 tons per hour from the winding depth of 1,412 ft. The drum is 16 ft. in diameter and 7 ft. wide between the flanges ; the duty cycle for this winder is shown in fig. 5. It is designed for single layer coiling of the winding ropes, and has a spirally grooved drumshell. Most components on this winder, including the main reduction gears, are similar to those of the upcast shaft equipment. The mechanical brakes operate on the same principles, but the hydraulic circuit is simpler because of the absence of clutch equipment.

FEATURES OF THE ELECTRICAL EQUIPMENT.

Electrically, the two winders are identical and embody the G.E.C. patented closed-loop speed control system which ensures an adequately close relationship between the steady rope speed and the position of the driver's lever. It also provides for an overriding torque limitation which ensures that excessive torques cannot occur on rapid movement of the control lever.

This system of control is notable for its outstanding performance at the very low speeds required for shaft inspection, rope changing and similar duties and when lowering heavy loads at slow speeds.

Low Speed Control.

For shaft inspection and rope changing the driver has no difficulty in maintaining a steady slow speed throughout the full depth of the shaft. During any period when only a very small torque is required, for example when the ascending and descending empty cages are nearing the position at which they pass each other, an automatic transition to "On"—"Off" control of the motor takes place. The smooth performance of the winder under these conditions is dependent upon the effective resistance range of the weir-type liquid controller, which is as high as 400 to 1.

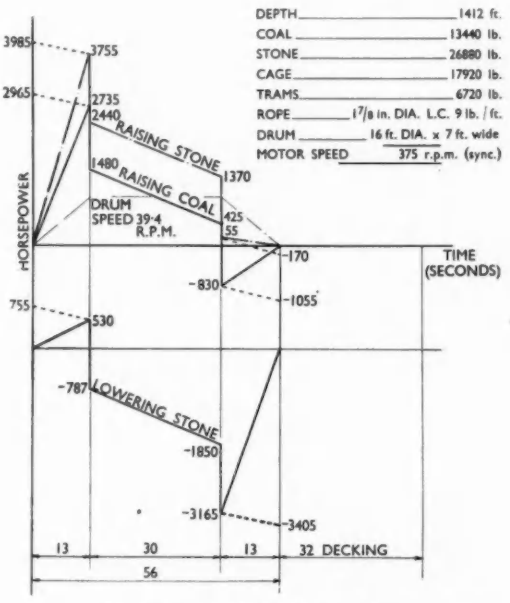

Fig. 5.—Duty cycle for downcast shaft.

Lowering Heavy Loads.

The system of dynamic braking is such that the heaviest loads can be lowered at creep speed without resorting to mechanical braking. With the mechanical brakes on and the control lever in the position of lowest speed, full d.c. excitation can be applied to the motor so that maximum dynamic braking is available immediately the brakes are released and the motor is free to rotate. Thus, as the maximum d.c. excitation is

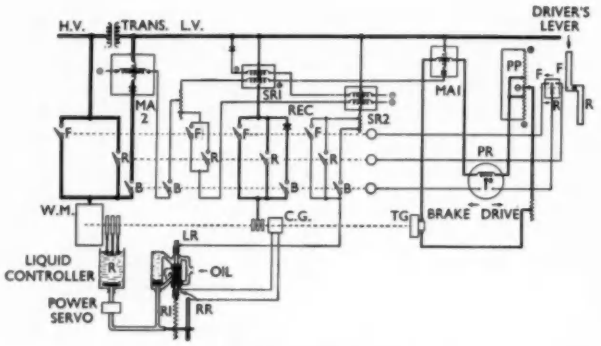

Fig. 6.—Upcast winder control circuit.

not dependent upon the current flowing in the rotor circuit, there is no undesirable acceleration during the period in which the rotor current is building up.

Protection.

The protection of the winders, which includes the Lilly controller already mentioned, follows standard practice and the various protective relays for each winder are grouped together in a separate floor-mounting cubicle, fig. 7.

Dynamic Braking and Speed Control System.

In the closed-loop system of control, the speed of the winder is determined by comparing, in the control circuit, the speed of the rope drum with that called for by a pattern potentiometer. Any lack of balance in the control circuit automatically results in an increase in the driving torque or the application of dynamic braking as may be required to increase or decrease the winder speed until the chosen speed is reached and the state of balance is restored.

Referring to the diagrammatic arrangement of the control circuit it will be seen that automatic variation of the rotor circuit resistance of the winder motor is effected through the medium of an oil servo-mechanism, the operating valve of which is governed by two control coils, acting in opposition to each other. Coil *LR*, which causes the resistance in the rotor circuit to be reduced, is energised by alternating current. When driving, this current varies with the speed error; during dynamic braking it is constant.

The other coil, *RR*, which serves to insert resistance, is excited from the stator or secondary winding of a control generator driven from the winder motor. At any given excitation of the control generator rotor, the voltage across this coil reflects that of the rotor of the main winder motor and varies in proportion to the slip or speed. The actual proportion is made dependent upon the speed error.

The driver's lever is arranged to move in a gate in the control desk, the slots for "forward" and "reverse" speed being separated by a small cross gate. The advantage of this feature is that there is a clear distinction between the "off" position, which is in the centre of the cross gate, and the "stop" position at the ends of the cross gate. Thus the driver can pull the lever back from full speed to the "stop" position without overshooting into the slot for the opposite direction of winding. In the "stop" position a high d.c. excitation is applied to the driving motor with the winder at standstill, thus providing the maximum dynamic braking previously referred to under the heading "Lowering Heavy Loads".

Operation.

The operation of the scheme will be appreciated by considering the sequence following three typical quick motions of the driver's lever.

"Stop" to "Half Speed Forward".

Movement of the driver's lever laterally to the end of the cross gate immediately sets up control circuits for the "forward" direction. Movement through the "forward" slot to the half-speed position causes the pattern potentiometer *PP* to apply half of its maximum voltage to the speed error signalling loop *TG-MA1-PR*. The current saturates the amplifier *MA1*, which produces its maximum output. At the same time the polarised relay *PR* closes contacts which set up the main contactor circuits for "driving".

Fig. 7.—Protective equipment for downcast winder.

With any speed error in excess of a predetermined value the magnetic amplifier *MA*1 delivers its maximum output to the control windings of the biased saturable reactors *SR*1 and *SR*2 via the forward or reverse contactors *F* and *R*. As the control winding opposes the bias winding of *SR*1, this reactor then gives minimum output and hence minimum excitation of the control generator *CG*.

On the other hand, as the control winding assists the bias winding of the saturable reactor *SR*2, the output from this reactor produces maximum excitation of the coil *LR* of the oil servo-mechanism. Thus the pull of coil *LR* is able to overcome that of coil *RR* and forces the servo to reduce the resistance of *R*1 until balance is obtained between the two coils. At the same time, the servo moves the liquid controller *R* to the value required to accelerate the winder motor *WM* at the chosen maximum torque. As the motor gathers speed the tacho-generator voltage rises. Since this voltage opposes the pattern voltage, the current in the speed-balancing winding of the amplifier *MA*1 falls ; no change takes place, however, in the output from this amplifier because it is so designed that it remains saturated so long as the difference between the tacho-generator voltage and the pattern voltage is large.

Acceleration continues, therefore, at maximum torque until the actual speed approaches the selected speed, when the output of the amplifier *MA*1 falls. This results in a rapid rise in the output voltage of the biased saturable reactor *SR*1 and thus causes the excitation of *GG* to increase. Coil *RR* then takes control and raises the resistance of *R*1 and *R* until the torque of the winder motor equals the load torque. Consequently the speed no longer increases.

As the wind proceeds, the down-going load increases with the length of rope and may ultimately exceed the up-going load. In this event the speed will rise by a small amount. When it exceeds that set by the driver's lever, the tacho-generator voltage will exceed the voltage derived from *PP*, and the current in the speed-balancing winding of *MA*1 and in *PR* will be reversed. The reversal of current in the speed-balancing winding has no effect, because the amplifier *MA*1 is non-directional and gives the same output for the given control current in either direction. The polarised relay *PR*, however, changes over its contacts, thus causing the main driving contactor to open and the main braking contactor to close.

As a result, the output from the amplifier *MA*1 feeds the saturable reactor *SR*1 and the magnetic amplifier *MA*2, while *SR*2 receives constant excitation. *MA*2 now supplies an increasing d.c. excitation to the stator of the winder motor (*WM*) until the braking effort is sufficient to balance the down-going load. During dynamic braking the reactor *SR*1 supplies d.c. excitation through the rectifier *REC* to the control generator *CG*. The relationship between the excitation of the winder motor and that of the control generator is so chosen that the resistance *R* is automatically kept near its optimum value, independently of the motor speed. The stability of the dynamic brake is thus assured under all conditions of operation.

On entering the retarding zone, the driver's lever is moved back to reduce speed. Even if the load is positive when this is done, the " pattern " voltage will be lower than the voltage of tacho-generator *TG*, and braking excitation (limited by the amplifier characteristics) is automatically applied. Maximum braking torque is developed upon any rapid backward movement of the driver's lever.

On reaching bank, full application of the mechanical brakes opens the dynamic-braking contactor.

" *Stop* " *to* " *Full Speed Forward* " (*Regenerative Braking*).

Acceleration to full speed takes place at maximum torque, as already described. Assuming that the wind is such that regenerative braking is possible, this will begin on a slight rise in speed above synchronism, the maximum pattern potentiometer voltage being set to permit the necessary increase without changing over to dynamic braking.

" *Full Speed Forward* " *to* " *Full Speed Reverse* " (*Reverse-current Braking or Plugging*).

The first movement of the driver's lever from " forward " towards " stop " will, of course, initiate dynamic braking, since the " pattern " speed will be less than the actual speed. When the lever passes through " stop " and " off " towards " reverse ", the " pattern " voltage increases once more in the same direction, but as the field of the tacho-generator *TG* is reversed the " pattern " and tacho-generator voltages are now additive. The polarised relay *PR*, therefore, restores the " driving " circuits, and reverse-current braking is applied at maximum torque under optimum conditions.

TECHNICAL LITERATURE

A digest of recent articles and papers by members of the G.E.C. and its associated companies

AUTOMATIC SETTING OF THE FLEXIBLE WALLS OF A LARGE WIND TUNNEL (735).*

By T. Barnes and C. R. Dunham (Research Laboratories).

The Proceedings of the Institution of Electrical Engineers, Vol. 105, *Part A, No.* 21, *pp.* 218-228, 1958.

To develop supersonic air flow in a wind tunnel it is usual to provide a nicely contoured constriction in the air passage ahead of the model test region, and it is necessary to alter the cross-section of this "throat" to cater for different air speeds. In the tunnel under consideration, the constriction is formed by two flexible steel plates, sliding between side walls and constrained to the required adjustable profile by a series of hydraulically-actuated screw jacks.

The paper deals with the electrical control system, for storing the necessary jack-setting data on punched tape, and releasing it to govern, simultaneously, the motion of every screw jack with the required degree of precision, so that the shape of the aerodynamic throat can be adjusted progressively throughout the air-speed range of the tunnel.

BRITISH MAGNETIC AMPLIFIER DEVELOPMENTS.

By D. A. Ramsay and B. W. Glover (Applied Electronics Laboratories).

Electrical Manufacturing, Vol. 62, *pp.* 56-62, *July*, 1958.

The British approach to the analysis of magnetic-amplifier circuits and their practical application provides grounds for fresh thinking in a basic area. Component selection to obtain maximum performance and the physical and electrical characteristics of amplifiers actually constructed are also given.

HIGH FREQUENCY GERMANIUM TRANSISTORS.

By J. S. Lamming (Research Laboratories).

Research, pp. 425-431, *November*, 1958.

This is the third article in a series on the technology of transistors. Previous articles dealt with alloy junctions and silicon transistors. The present article discusses the design theory of high frequency transistors in an elementary manner and several techniques for producing high frequency transistor structures are briefly described.

STRUCTURAL, DIELECTRIC AND OPTICAL PROPERTIES OF FERROELECTRIC LEAD METANIOBATE (770).*

By M. H. Francombe and B. Lewis (Research Laboratories).

Acta Crystallographica, Vol. 11, *Part* 10, *pp.* 696-703, *October*, 1958.

X-ray structural, electrical and optical studies have been made of both single-crystal and ceramic specimens of ferroelectric $PbNb_2O_6$. High-temperature X-ray powder data show that above 560 deg. C., the Curie temperature, the structure changes from orthorhombic to tetragonal, and that the paraelectric structure is closely related to that of certain tetragonal alkali tungsten bronzes.

Plate-like single crystals of $PbNb_2O_6$ show a domain structure indicating ferroelectric polarisation along the (010) axis. Along this axis and along (100), but not along (001), there is a sharp permittivity maximum at the Curie temperature.

INDUSTRIAL PRACTICE IN COLD PRESSURE WELDING.

By J. A. Donelan (Research Laboratories).

British Welding Journal, pp. 5-12, *January*, 1959.

Cold pressure welding has been used as an industrial process for several years. The principles of cold welding, preparation of metal surfaces for welding, and the influence of die design on weld strength are described.

Applications of the process to the welding of aluminium and copper foil, sheet, wire, rod, and tubes for the electrical, electronic and other industries are reviewed.

STRUCTURE-CELL DATA AND EXPANSION COEFFICIENTS OF BISMUTH TELLURIDE (780).*

By M. H. Francombe (Research Laboratories).

British Journal of Applied Physics, Vol. 9, *pp.* 415-417, *October*, 1958.

Accurate measurements of the structure-cell parameters of bismuth telluride, Bi_2Te_3, have been made using annealed powders and etched rods cut from single-crystal ingots. Previously reported anomalies in the X-ray powder intensity data are found to originate entirely in preferred orientation of the crystallites.

A study of the thermal expansion of the unit cell over the temperature range −195 to 400 deg. C. has revealed a marked anisotropy between the axial expansion coefficients, that for the c axis ($22{\cdot}2\times10^{-6}$ per deg. C. at 20 deg. C.) being almost twice that for the a axis ($12{\cdot}9\times10^{-6}$). Near 200 deg. C. changes occur in both the principal axial expansions, comparable with those observed at low temperatures in certain hexagonal metal structures.

A MICROWAVE REFLECTOMETER DISPLAY SYSTEM FOR 7,500 TO 11,000 Mc/s (782).*

By J. C. Dix and M. Sherry (Research Laboratories).

Electronic Engineering, Vol. 31, *No.* 371, *pp.* 24-29, *January*, 1959.

An X-band reflectometer display system which has recently been developed is described. This instrument gives a continuous display of the match of an X-band waveguide component over a frequency band of 7,500 to 11,000 Mc/s.

The basic principle is that when the frequency is changed

the variation of the modulus of reflection coefficient of a test load is indicated by the change in level of the reflected wave if the amplitude of the incident wave is maintained constant and independent of frequency.

THE THEORY OF BALLAST TUBES OR BARRETTERS (783).*

By R. O. Jenkins (Research Laboratories).

British Journal of Applied Physics, Vol. 9, *pp.* 391-394, *October*, 1958.

The theory is based on a simple graphical method of solving the equation of thermal equilibrium of an electrically heated wire in a gas-filled enclosure. The results account for the main operating characteristics and have accurately predicted the ratings of various low voltage barretters. It is also shown why, in practice, barretters have always consisted of an iron wire in hydrogen.

THE MAGNETIC SPECTRA OF SOME FERRITES.

By E. A. Faulkner and J. F. Werner (Research Laboratories).

Journal of Scientific Instruments, Vol. 35, *pp.* 474-475, *December*, 1958.

Measurements have been made of the complex initial permeability ($M=\mu'-j\mu''$) of ferrites in the range 1·0-3,300 Mc/s, special attention being given to the accuracy and reproducibility of the results, which are in general about ± 1 per cent.

DEUTERIUM-FILLED THYRATRONS.

By K. G. Cook and G. G. Isaacs (Research Laboratories).

British Journal of Applied Physics, Vol. 9, *pp.* 497-498, *December*, 1958.

Hot cathode hydrogen thyratrons are now widely used as pulse modulators in radar equipments and recently have been used as grid controlled rectifiers. The authors show that the use of deuterium as a filling in thyratrons and grid-controlled rectifiers appears to offer considerable advantages over hydrogen.

THE GRID EMITTING PROPERTIES OF TITANIUM (787).*

By J. A. Champion (Research Laboratories).

British Journal of Applied Physics, Vol. 9, *pp.* 491-495, *December*, 1958.

Experiments are described in which the emission from thin films of barium and barium oxide deposited on titanium is compared with that from similar deposits on tungsten. With deposits of both barium and barium oxide the emission from titanium is very much less than that from tungsten throughout the temperature range investigated (700-1,000 deg. C.). Above about 900 deg. C. the evaporation of titanium will poison the emission of an adjacent oxide cathode, but it is concluded that from 700 deg. C. up to this temperature titanium would possess good grid emission suppression properties.

THE DETERMINATION OF IMPURITIES IN CARBON DIOXIDE BY GAS CHROMATOGRAPHY, WITH SPECIAL REFERENCE TO COOLANT GAS FOR NUCLEAR REACTORS (790).*

By D. G. Timms, J. H. Konrath and R. C. Chirnside (Research Laboratories).

The Analyst, Vol. 83, *No.* 992, *pp.* 600-609, *November*, 1958.

It has been shown that, with a 25-ml. sample, hydrogen, argon, oxygen, nitrogen, methane and carbon monoxide present at levels as low as 5 to 20 p.p.m. in carbon dioxide can be determined by a gas-chromatographic method.

Special features of the technique are the use of a molecular sieve as the solid adsorbent, the high speed of analysis and the use of a katharometer of high sensitivity.

WAVE MATRICES APPLIED TO A PERIODICALLY LOADED TRAVELLING-WAVE TUBE (814).*

By D. E. T. F. Ashby (Research Laboratories).

Journal of Electronics and Control, Vol. 5, *No.* 4, *p.* 338, *October*, 1958.

While investigating the design of filter helices for inhibiting backward-wave oscillations in travelling-wave tubes a method of analysis was developed in which a T.W.T., periodically loaded with shunt admittances, is described by four-by-four matrices whose function and use are similar to the two-by-two wave matrices used in four-terminal network theory. The derivation of these matrices is shown and an expression derived for the conditions necessary for this system to oscillate due to feed-back caused by reflections from the periodic discontinuities.

AN APPROXIMATE THEORY FOR DETERMINING THE CHARACTERISTIC IMPEDANCES OF ELLIPTIC WAVEGUIDE (815).*

By R. V. Harrowell (Research Laboratories).

Journal of Electronics and Control, Vol. 5, *No.* 4, *p.* 289, *October*, 1958.

In an investigation into the behaviour of an elliptic window in rectangular waveguide it was necessary to know the characteristic impedance of elliptic guide. An approximate theory for this is derived, and design data presented in graphical form.

THE EFFECT OF HEAT TREATMENT ON THE BREAKDOWN CHARACTERISTICS OF SILICON *pn* JUNCTIONS (821).*

By A. R. Plummer (Research Laboratories).

Journal of Electronics and Control, Vol. 5, *No.* 5, *p.* 405, *November*, 1958.

Silicon *pn* junctions have been studied which exhibit soft breakdown in the reverse characteristic, and experiments are described which show that this can be caused not only by surface conditions, but also by unsuitable bulk properties resulting from heat treatment of the silicon. An explanation for this effect is suggested.

THE EFFECT OF STRAIN ON THE THERMOELECTRIC PROPERTIES OF A MANY-VALLEY SEMICONDUCTOR (824).*

By J. R. Drabble (Research Laboratories).

Journal of Electronics and Control, Vol. 5, *No.* 4, *p.* 362, *October*, 1958.

The electrical conductivity and thermoelectric power of a many-valley semiconductor are considered as functions of strain, neglecting all effects other than those due to carrier transfer between valleys. For non-degenerate materials a general treatment is given and it is shown that the absence of other effects can be checked by the condition that the trace of the conductivity tensor is unaltered by the strain.

PHOTOCHEMICAL EFFECTS AND THE EFFECT OF OXYGEN ON PHOTOCONDUCTING CADMIUM SULPHIDE CRYSTALS (829).*

By J. Woods (Research Laboratories).

Journal of Electronics and Control, Vol. 5, *No.* 5, *p.* 417, *November*, 1958.

Single crystals of cadmium sulphide can be activated to give high photoconductive sensitivity in a variety of ways.

Experiment shows that crystals containing a non-stoichiometric excess of cadmium in the form of sulphur vacancies are inherently unstable. Their photoconductivity decays under illumination and on exposure to an ambient atmosphere containing oxygen. This instability can be eliminated by using an activation treatment which does not produce sulphur vacancies.

CHARACTER AND COMPROMISE IN HOTEL LIGHTING.

By C. Dykes-Brown and W. R. Stevens.

Transactions of the Illuminating Engineering Society, Vol. 23, *No.* 4, *pp.* 179-198, 1958.

The areas of a hotel used primarily by the staff are working places in which the lighting can follow well-established practice. The areas used by guests present much more difficulty because the requirements are often nebulous and the possible methods of lighting are many and varied. The authors give some specific recommendations for staff areas, but for guest areas the broad requirements are stated, some lighting principles discussed and typical solutions illustrated.

DEVELOPMENTS IN VACUUM SINTERING FURNACES.

By B. M. Donovan (Research Laboratories).

Powder Metallurgy, No. 1/2, *pp.* 104-113, 1958.

Until recently industrial powder metallurgy has been concerned mainly with the making of articles from copper alloys, molybdenum, tungsten, iron and steel, refractory metal carbides, and certain magnetic materials. Over the last few years the techniques of powder metallurgy have been used to prepare in the laboratory an increasing number of materials which are highly reactive and cannot be sintered in either hydrogen or cracked ammonia without the formation of hydrides or nitrides or oxides. For such materials sintering in vacuum has proved advantages which have led to its increasing adoption, in parallel with vacuum treatments, in other fields of metallurgy.

TRENDS AND DEVELOPMENTS IN DISCHARGE LAMPS.

By H. G. Jenkins (Research Laboratories).

Light and Lighting, Vol. 51, *No.* 12, *pp.* 391-402, *December*, 1958.

Developments in discharge lamps have been so numerous that it is timely to review recent progress and perhaps to see what the future is likely to bring forth. This article sets out to do this for the benefit of both the lighting engineer and of the user. In addition to the more important discharge lamps, electro-luminescence, the radioactive lamp and some recent circuit developments are discussed.

THERMOELECTRIC REFRIGERATION.

By D. A. Wright (Research Laboratories).

The New Scientist, Vol. 5, *pp.* 351-353, *February* 12, 1959.

Semiconductors are materials which will conduct electricity although they have a much higher electrical resistance than metals. Some of them have properties which make them suitable for use in thermoelectric cooling, and possible applications are being actively investigated.

THE STATISTICIAN AND SAMPLE TESTING.

By A. N. James (Research Laboratories).

Bulletin of the Institute of Physics, pp. 182-188, *August*, 1958.

It is generally conceded that tests have to be made on batches of materials or on manufactured goods themselves at some stage or stages of a production process.

The purposes to which the data from these tests are put may be divided roughly into two categories :

(*a*) Tests whose sole purpose is to provide information.
(*b*) Tests, the results of which are used to make definite decisions.

The purpose of this paper is to discuss the characteristics of the second type ; these tests, where they involve taking samples, are usually called sampling schemes.

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